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Welding Refractory Metal Alloys For Space Power System Applications

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ABSTRACT

The weldability of promising high strength refractory metal alloys was determined with emphasis on the reliability requirements of space power systems. Eight columbium base alloys, three tantalum base alloys and one tungsten alloy, W-25 Re, were evaluated.

Significant differences in welding response, as measured by weld ductility, were noted between alloys. Alloys were welded over a wide range of welding conditions by both the tungsten arc and electron beam processes. Interestingly, variability of weld ductility for any one alloy appears to be an innate alloy characteristic since ductility response did not correlate strongly with intentional weld process variations.

Alloys were welded in both sheet and plate thicknesses. Restrained welds were used to demonstrate simple weldability while butt welds were used for mechanical evaluation.

Generally good weldability was demonstrated by all the alloys even though weldability limitations were exceeded for some within a nominal range of welding conditions. As a group the tantalum alloys had significantly greater weldability than the columbium alloys.

Little actual difference in room temperature strength was noted for these alloys, presumably because of their compositional similarities. At elevated temperatures the tantalum alloys were generally stronger than the columbium alloys. Within any one alloy group, those containing reactive element solute additions of hafnium or zirconium are considerably stronger. Joint efficiencies for all alloys were nearly 100 percent through 2400°F. All of the columbium alloys were shown to respond to post-weld annealing and, based on these results, post-weld annealing is generally recommended for optimum ductility and to enhance thermal stability. The tantalum alloys were considerably more stable in this respect.

INTRODUCTION

Refractory metal alloys will be used extensively in contemplated advanced space electric power systems. Typical applications will include working fluid containment, high temperature cladding, and turbo-electric power conversion system components such as turbine blades, discs, and nozzles. Their attractiveness for these applications stems primarily from a combined resistance to corrosion by liquid and gaseous alkali metals, and retention of strength at temperatures above 2000°F. Their most severe shortcomings, poor oxidation resistance and adverse ductility response to atmospheric contamination, are avoided by application in the high vacuum space environment.

The present generation of refractory metal alloys was developed primarily for short time aerospace applications. In contrast, space power systems require reliable operation for long time periods. Thus, space power systems represent a considerable change in emphasis with regard to material properties since long time creep strength and thermal stability, as well as fabricability and resistance to liquid metal corrosion are major alloy selection criteria. The awareness of these requirements prompted the National Aeronautics and Space Administration to sponsor a number of programs designed to upgrade the current knowledge of the behavior of refractory metal alloys in long time and high temperature applications.

Because of difficulties experienced in welding first generation refractory metal alloys, the need for a uniform determination of the comparative weldability of recently developed alloys was recognized. Hence, a program to evaluate refractory metal alloy weldability was undertaken. * The results are summarized in this paper. A thermal stability study which involves 10,000 hour testing is also included in this program but is not yet complete. The thermal

*Reference Contract NAS 3-2540, "Determination of the Weldability and Elevated Temperature Stability of Refractory Metal Alloys," Technical Manager: P. E. Moorhead.

stability study complements the weldability study since it is in the weld metal and adjacent thermally disturbed base metal that damaging instabilities are most likely to occur.

ALLOYS

The fourteen alloys selected for inclusion in this program are listed in Table 1. All were purchased in the recrystallized condition and in uniform sheet and plate thicknesses of 0.035 and 0.375 inch respectively. This was done to assure a comparable evaluation. The eight columbium base alloys comprise the major portion of this group reflecting the emphasis of government and industry sponsored alloy development efforts. This emphasis stems from the importance of the density advantage of columbium over tantalum (0.31 lb/cu. in. vs. 0.60 lb/cu. in.) in aerospace applications and also availability. Inclusion of the two high strength tantalum alloys, T-111 and T-222, reflects a growing interest in tantalum systems because of their greater fabricability combined with promise of an eventual tantalum system with a high temperature strength-density ratio superiority. The solid solution strengthened Ta-10W alloy was included as a reference alloy. The three tungsten alloys were included primarily to ascertain the extent to which the state of the welding art would have to be advanced to join extremely brittle materials, and to determine if recent improvements in tungsten technology would translate into improved weldability. Hence, both unalloyed tungsten and tungsten-25 rhenium were produced using recently developed techniques for conversion from arc cast ingots. The arc cast material was selected because it provided porosity free welds in a preliminary TIG weld comparison with several grades of powder metallurgy tungsten. Sylvania "A" is the only powder metallurgy product. Other alloys were produced by vacuum arc and/or electron beam melting. Except for the tungsten alloys and two columbium alloys, AS-55 and D-43Y, all these alloys are considered to be commercially available.

TABLE 1 - Alloys Included in the Weldability and Thermal Stability Evaluations

<u>Alloy</u>	<u>Nominal Composition Weight Percent</u>
AS-55	Cb-5W-1Zr-0.2Y-0.06C
B-66	Cb-5Mo-5V-1Zr
C-129Y	Cb-10W-10Hf+Y
Cb-752	Cb-10W-2.5Zr
D-43	Cb-10W-1Zr-0.1C
FS-85	Cb-27Ta-10W-1Zr
SCb-291	Cb-10W-10Ta
D43 + Y	Cb-10W-1Zr-0.1C+Y
T-111	Ta-8W-2Hf
T-222	Ta-9.6W-2.4Hf-0.01C
Ta-10W	Ta-10W
W-25 Re	W-25Re
W	Unalloyed
Sylvania "A"*	W-0.5Hf-0.02C

* NOTE: All alloys from arc-cast and/or electron beam melted material except Sylvania "A"

PROGRAM OBJECTIVES

The basic objective of this study was to provide the essential information required for rating the alloys on the basis of overall weldability. The tests employed were chosen on the basis of known responses of refractory metal alloys to welding. Ductility impairment represents an important area of investigation in this respect. As a general rule the unalloyed base metal, except tungsten, is very ductile, but both alloying and subsequent welding cause successive losses in ductility. A sensible measure of ductility, and of ductility impairment occurring with welding is provided by the ductile-to-brittle transition temperature. The transition behavior is characteristic of the body centered cubic refractory metals, and the transition temperature is easily measured by bend testing. Hence, bend testing was emphasized in this program. In addition, restrained weld tests were employed and alloys were welded as sheet and plate to demonstrate basic weldability. Manual TIG welding, automatic TIG welding, and electron beam welding were employed since they represent the applicable joining processes for these alloys. Weld strength was determined and compared with base metal strength at ambient and elevated temperatures. The entire evaluation included appropriate and extensive use of metallography to help correlate weld structure to weld properties.

The weldability phase was designed to provide a comparison of the alloys based on the following information:

1. A measure of weld hot tear sensitivity.
2. The degree of impairment of alloy ductility resulting from welding.
3. The range of weld properties obtainable through variation in welding parameters and processes and a determination of plausible cause and effect relationships.
4. A rough delineation of change in weldability and weld properties with section size.
5. The extent to which base metal properties can be recovered by post weld annealing.
6. Ambient and elevated temperature tensile joint efficiency.

TECHNICAL APPROACH

Early observations made on refractory metal alloys indicated that welding parameter selection could greatly influence the bend ductile-brittle transition temperature. Since bend testing would be used extensively in this program, an evaluation of the effect of weld parameters on bend ductile-brittle transition temperatures was the first welding objective. One important reason for investigating these effects was to establish a uniform method of selecting welding parameters for preparation of specimens for the successive evaluation phases of this program, i. e. the post weld anneal, base line tensile, and thermal stability studies. For this purpose, the parameter series was expected to provide an optimum set of weld parameters for each alloy.

In selecting TIG weld parameters for evaluation, the effects of variation in weld freezing rate, cooling rate, and unit weld length heat input were emphasized rather than current, speed, and voltage per se. This approach tended to vary in a qualitatively predictable manner the time-temperature relations controlling metallurgical reactions in the heat affected zone as well as its size. Similarly, these factors most significantly affect the important weld characteristics of grain and cell size, grain orientation, and solute redistribution (coring). Hence, in addition to optimizing weld parameters, this approach was designed to identify essential structural interactions occurring with welding and their effect on weld properties.

A typical TIG welding schedule is shown in Figure 1. Twelve selected welding conditions are indicated in this figure. The range of parameters investigated was limited to the generally practical range of conditions which would be encountered in hardware fabrication. Weld freezing and cooling rates are closely associated with weld speed and clamp spacing. Hence, these were chosen as variables. The heat input per unit weld length is related to weld size as well as weld speed. Hence, two different weld sizes were used to aid in identifying total heat input effects. Welding currents were selected to obtain the desired weld sizes. The

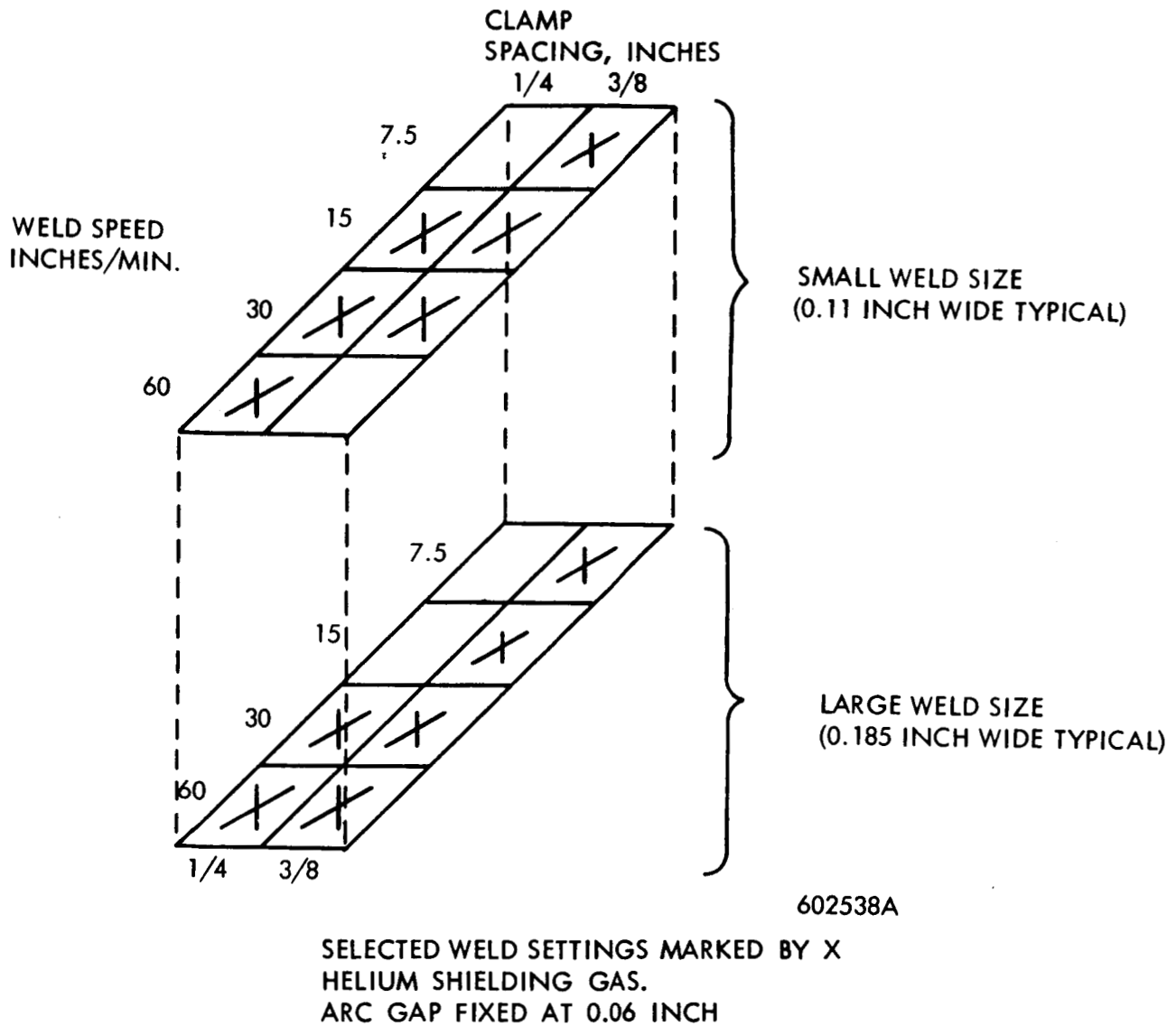
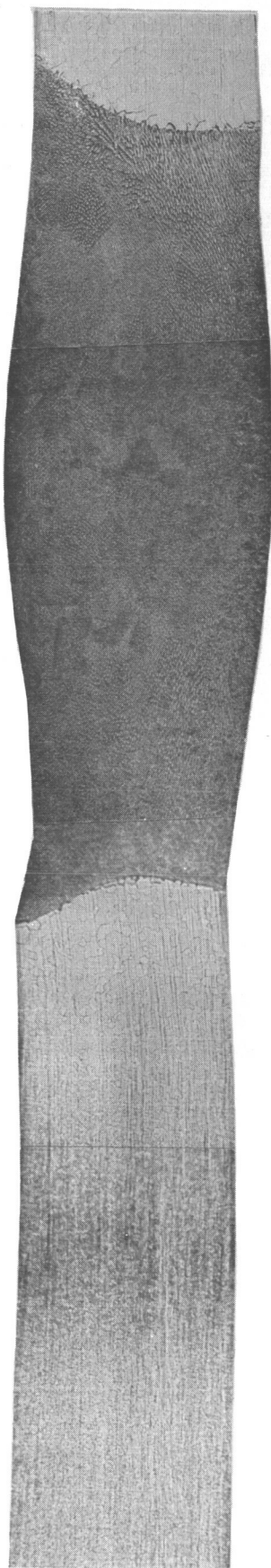


FIGURE 1 - Typical TIG Sheet Butt Weld Schedule for
Welding Optimization Study

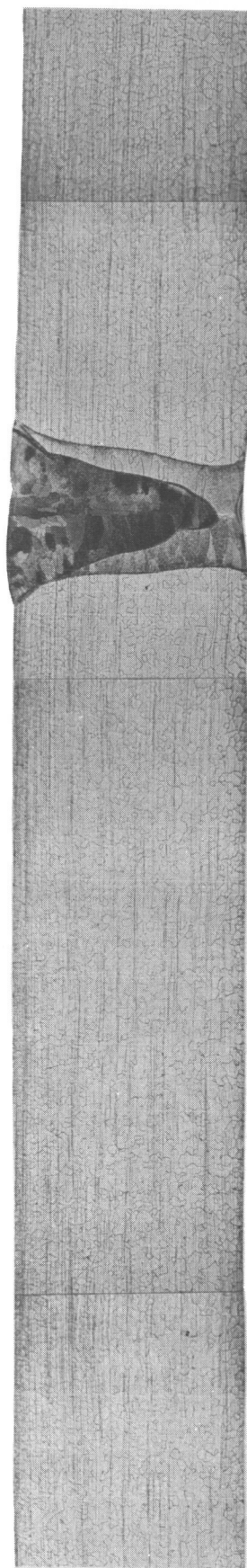
target weld sizes were standardized for all the alloys at 0.0039 and 0.0065 square inches cross-sectional area for the small and large welds respectively. These represent welds having average widths of 0.11 and 0.18 inches. Standardization of weld sizes, in addition to simplifying the thermal analysis, represents a practical method for comparing alloys since any one application requires a specific fixed weld size regardless of the alloy selected.

All TIG welding variables other than welding speed, clamp spacing, and weld size (amperage) were not varied since they were considered of secondary importance both in realizing the screening objectives and evaluating alloy thermal response characteristics. The influence of arc gap, electrode configuration, and shielding gas composition on weld configuration was recognized and these were held constant. Electrodes were machine ground to a fixed configuration and were extended one inch from the electrode holder with a 0.060 inch arc gap. Helium was used exclusively for shielding. Actual butt welds, not bead-on-plate welds, were produced throughout these studies to assure that results would be oriented towards hardware fabrication.

The scope of the high voltage electron beam welding evaluation was the same as for TIG welding. Twelve weld parameter combinations were selected. Again, the effect of freezing rate, cooling rate, and unit length heat input was emphasized. Parameter boundary conditions were selected to encompass the reasonable practical range of actual applications, and, within the limit of alloy to alloy variability, to provide sound, uniform, and defect free welds. In the overall program perspective, electron beam welding provides the means of joining a given thickness of material with a minimum sized weld and, hence, minimum total heat input. This size contrast is apparent in Figure 2 which shows corresponding TIG and EB welds. For the 0.035 inch standard sheet thickness, EB welds require about 1/3 as much energy at low speeds as compared with TIG welds and about 1/10 as much at higher speeds (> 50 ipm). Hence, electron beam welds generally display improved weldment characteristics. To fully realize the advantage of high voltage (150 KV) welding, weld size, under any given set of conditions, was always minimized by focusing the electron beam to its smallest diameter (highest energy density).



T-111



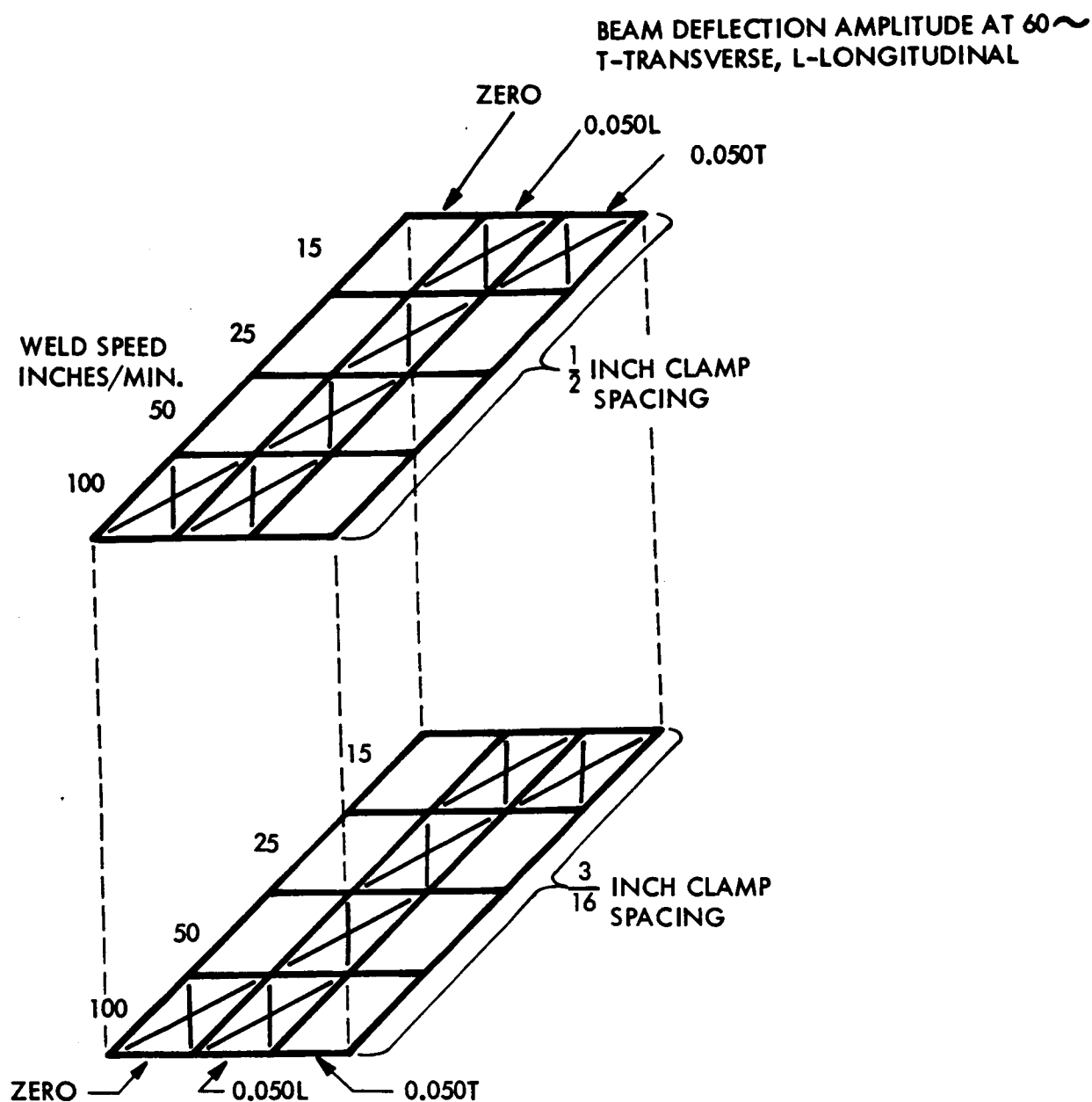
T-222

FIGURE 2 - Typical Sheet Butt Weld Configurations. Top, TIG Weld, Bottom, EB Weld
(35X)

Figure 3 shows a typical parameter series sheet butt weld schedule for electron beam welding study. All electron beam welding was done at the full 150 KV beam voltage. Preliminary trials showed that varying voltage in the 2 KW Hamilton-Zeiss gun over a practical range, 70 KV to 150 KV, while using the ground rule minimum beam diameter, did not influence weld configuration. Penetration trials at the various weld speeds were used to establish welding current which was set at 110% of the full penetration current. This provided an approximately constant weld size over the entire weld speed range for any one deflection pattern. The use of cyclic beam deflection is a practical concession since in most applications this type of beam control is necessary to produce sound welds. Two clamp spacings were used. The wide weld clamp spacing provides merely the weldment holding function while the narrow clamp spacing proves beneficial in restricting the weld heat affected zone and in increasing cooling rates. The weld speed range covered provides a general trend of increased welding efficiency with increased speed and therefore lower unit weld length heat input. Additional settings providing extremes of heat input, a maximum at 15 ipm and 0.050 transverse deflection and a minimum at 100 ipm and zero deflection, are included in this schedule. The same basic objectives are satisfied in the EB weld schedules as the TIG weld schedule.

Manual welding of the refractory metal alloys, primarily as 0.375 inch plate, rounded out the welding phase of this program. The manual plate welding complements the machine sheet welding study in three important respects: It measures weldability on the basis of the most flexible joining technique for fabricating structures; it is on the opposite end of the heat input spectrum from EB welding; and it provides an overall measure of the effects of section size on alloy fabricability. An important aspect of thick section welding is the modification of the cast substrate, or first weld passes, as successive weld passes are applied. These effects can be evaluated only by multi-pass welding.

In chronological order, the sheet and plate welding studies were followed by the post weld annealing study. Again, ductility response as measured by shifts in the bend ductile-brittle transition temperature was used to determine the effects of annealing. In contrast to the



NOTES:

1. BEAM ACCELERATING VOLTAGE = 150 KV, ALL WELDS
2. BEAM CURRENT SET AT 110 % OF FULL PENETRATION POWER

603941-1B

FIGURE 3 - Typical EB Sheet Butt Weld Schedule

weld parameter study, the emphasis in this effort was not so much to determine a total spread in ductility, but rather to identify optimum annealing schedules. The rationale for this emphasis stemmed from earlier reported data for the binary Cb-1Zr alloy.¹ Post weld annealing of Cb-1Zr welds was required to avoid detrimental aging during elevated temperature exposure. This aging response was associated with the reactive metal alloying addition. Since such additions are present in most of the alloys evaluated in this program, the need for post weld annealing was presumed. Hence, identification of an optimum annealing schedule, rather than simply on evaluation of annealing response, was the objective of this effort.

The tensile evaluation of these alloys was conducted using optimum weld parameters and optimum annealing schedules for both base and weld metal specimens. Hence, the alloys are compared in their most ductile, and presumably most fabricable, condition. Sheet base metal and transverse TIG weld specimens were tested using conventional techniques at room temperature and at 1800°F, 2100°F, and 2400°F. The elevated temperature tests were conducted in a 10^{-6} torr vacuum. Longitudinal and transverse welded plate specimens were tested at room temperature in the post weld annealed condition. The primary purpose of tensile testing was to compare the alloys on the basis of joint efficiency over a significant temperature range.

SPECIAL PROCEDURES AND EQUIPMENT

TIG SHEET WELDING

TIG welding was conducted using a 50 cubic foot, vacuum-purged weld chamber. This chamber can be evacuated rapidly, and a pressure of 5×10^{-5} torr with a conventionally acceptable leak rate of 5×10^{-4} torr (1 minute pressure rise) requires pumping for less than one half hour. This leak rate, or apparent leak rate since it measures both leaks and chamber outgassing, was found to result in unacceptable moisture levels in the backfilled chamber. This occurs because moisture is the major outgassing component. In this program overnight pumpdowns complemented by a heat lamp bake-out cycle were used to provide an acceptable vacuum purge of 5×10^{-6} torr pressure and 3×10^{-5} torr/min leak rate. Ultra-high purity helium was used for backfilling providing a total active impurity level in the chamber atmosphere of about 1 ppm. During welding both oxygen and moisture were continuously monitored. Welding was discontinued when either impurity reached 5 ppm. Development of the atmosphere measurement and control techniques and a demonstration of the adequacy of the procedure employed has been previously reported and, hence, is not repeated here.² The sheet butt weld clampdown fixtures and traversing table are shown in Figure 4. A clamp force of approximately 100 lbs/in. is provided by this fixture. The clamp inserts are made of molybdenum and the backup bar of copper. The stationary torch is water-cooled. Welding current was provided by a three phase direct current Vickers 300 ampere welder, equipped with a precision weld programmer and high frequency arc starter. Straight polarity was used exclusively.

ELECTRON BEAM WELDING

A 2 KW, Model W0-2, Hamilton-Zeiss electron beam welder was used for sheet butt welding. This is a variable high voltage unit capable of 150,000 volt operation with a maximum beam current of 13.5 ma. The beam has a fine focus control (0.010 inch diameter at full power) and can be oscillated to 60 cps. A power density of 25,000 KW per square inch can be realized.

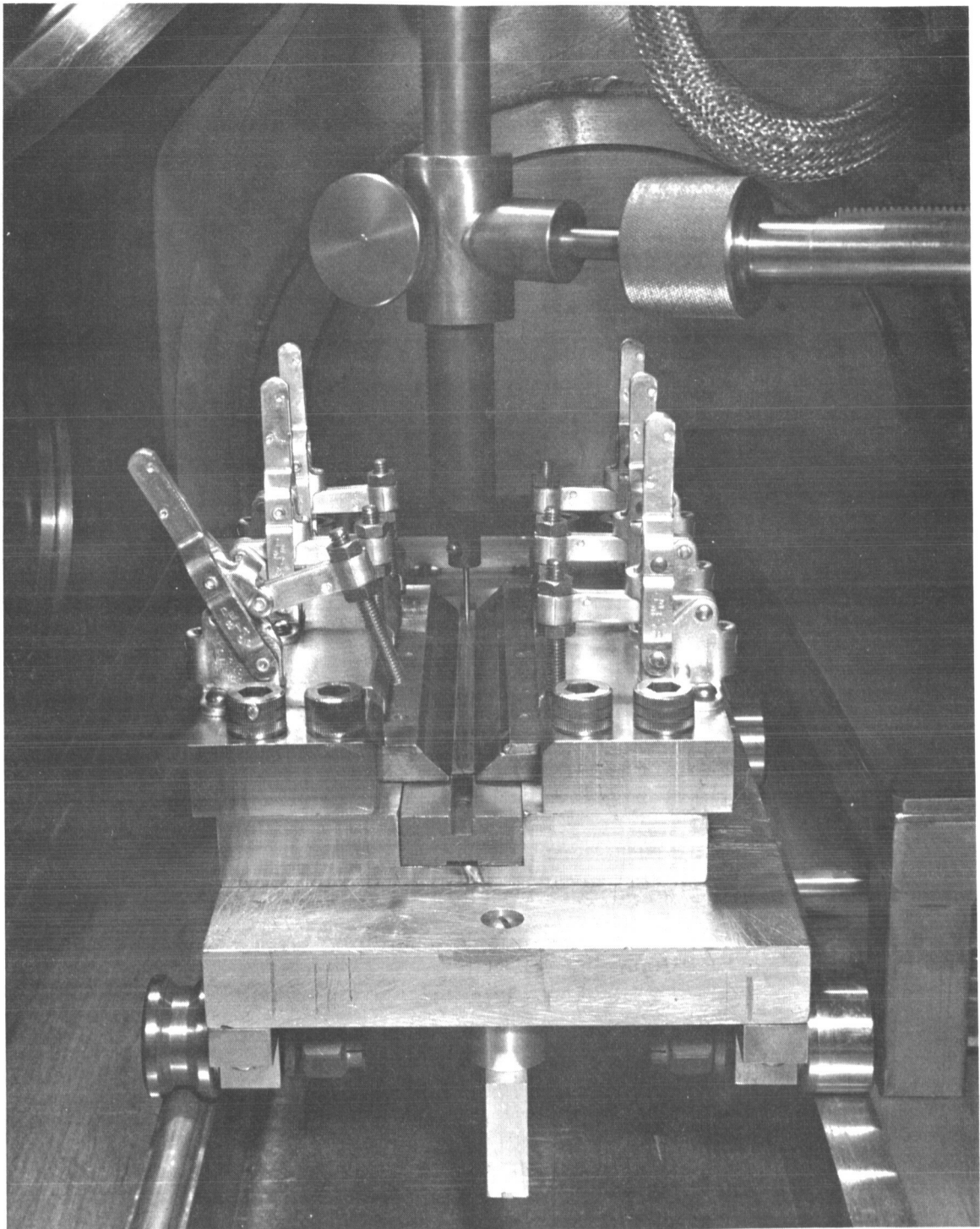


FIGURE 4 - TIG Butt Weld Tooling

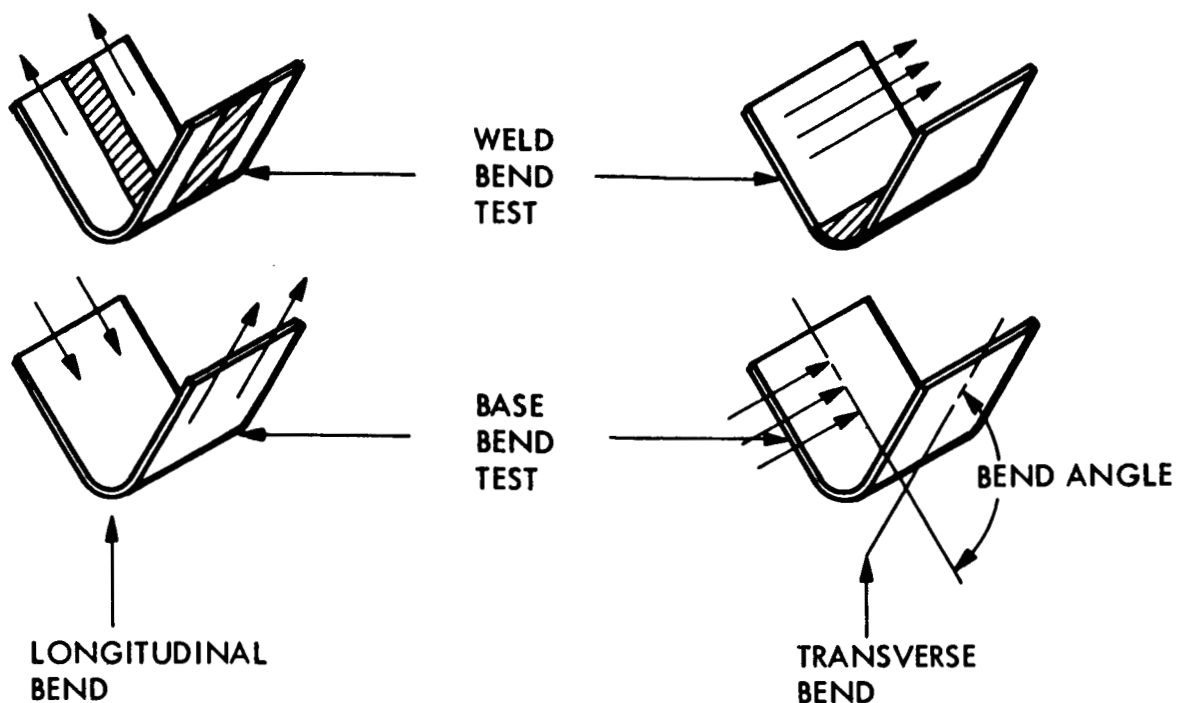
Prior to welding, beam current control calibrations were made at the workpiece level using a Faraday cup. This procedure is used to be certain that electron losses between the emitter and target are minimized. Without calibration the indicated beam power may not be realized at the workpiece. As with TIG welding, overnight chamber pumpdowns were used with internal heat lamp bake-out to obtain pressures for welding in the low 10^{-6} torr range. Separate aluminum fixtures were used for each selected clamp spacing. Since full beam penetration was used, a backup strip of the alloy being welded was placed in the fixture backup groove. This protected the weld underside from vapor deposition by aluminum from the fixture.

SHEET BEND TESTING

The bend test parameters are shown in Figure 5. Note that the weld and rolling direction orientation were held constant in this program. A 1t bend radius was used almost exclusively. A group of bend test curves for FS-85 electron beam welds are shown in Figure 6. This is a typical example of the type of curves generated by bend testing. Testing procedures are fairly straightforward. Specimens are tested with as-welded surfaces with the face of the weld in tension. Specimens are bent to an angle of 90 to 105° after springback at a number of selected temperatures spanning the transition range. The bend ductile-to-brittle transition temperature is identified as the lowest temperature at which a 90° bend can be made without cracking on the tension side of the specimens. Specimens are checked for cracks using visual and dye penetrant inspection.

PLATE BUTT WELDING

All plate welding was accomplished by manual TIG welding in the same chamber used for automatic sheet butt welding. Again, ultra-high purity helium was used as the welding gas and the atmosphere was monitored during welding. The acceptable maximum moisture level was set at 10 ppm as compared with 5 ppm for sheet welding. This was necessary for practical reasons since increased outgassing of interior weld chamber surfaces, the primary source of water vapor, occurred with the high heat input of plate welding.



NOTE: ARROWS SHOW ROLLING DIRECTION

THICKNESS, $t = 0.035$ INCH

WIDTH = $12t$

LENGTH = $24t$

TEST SPAN = $15t$

PUNCH SPEED = 1 IPM

TEMPERATURE - VARIABLE

PUNCH RADIUS - VARIABLE, GENERALLY $1t$, $2t$, $4t$, or $6t$

BEND DUCTILE TO BRITTLE TRANSITION TEMPERATURE =
LOWEST TEMPERATURE FOR $90^\circ +$ BEND WITHOUT CRACKING

596924A

FIGURE 5 - Bend Test Parameters

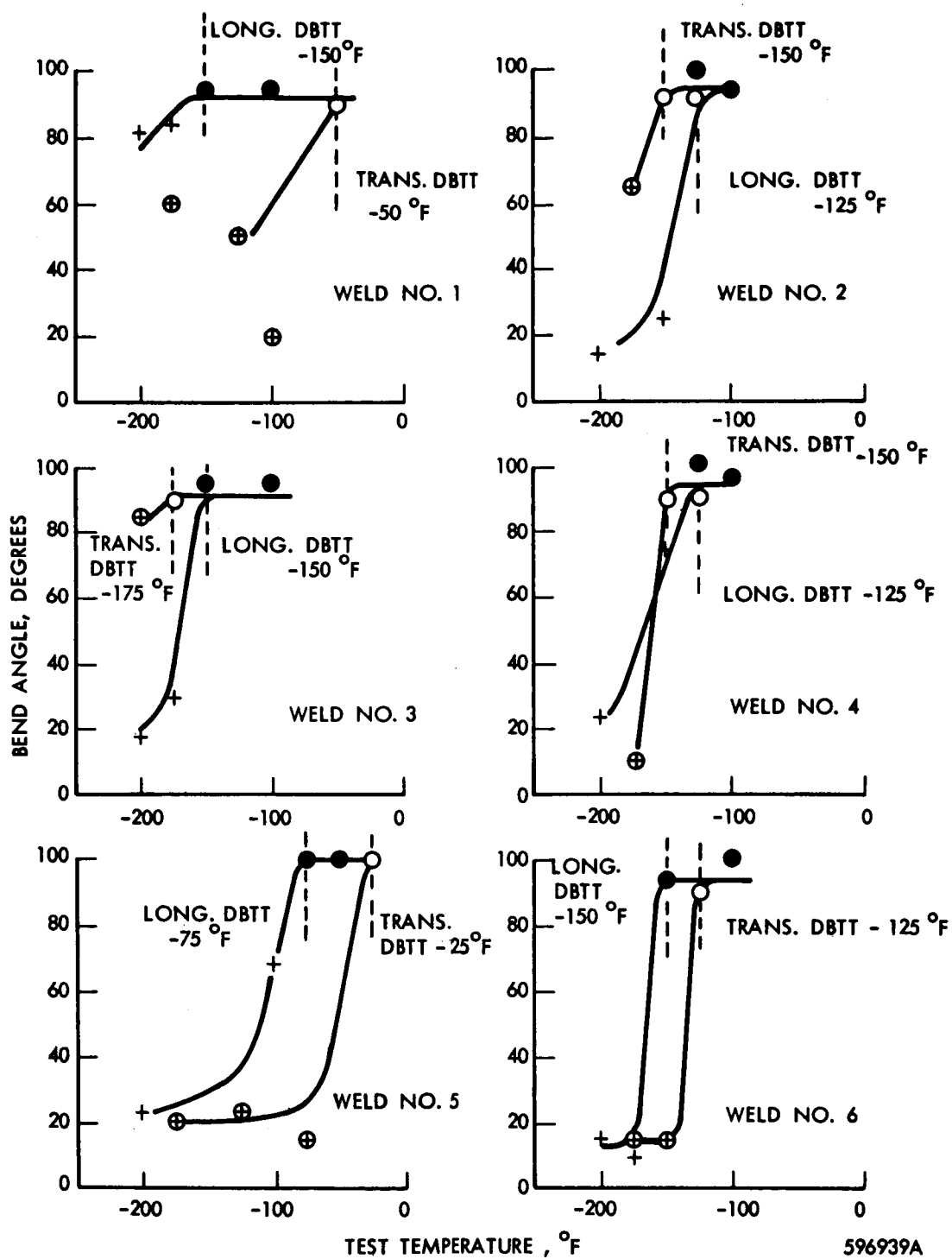


FIGURE 6 - FS-85 EB Weld Bend Test Results

To minimize moisture outgassing and for operator comfort, extensive internal chamber cooling was employed. A water-cooled convection heat exchanger and specially designed water-cooled welding torch and platen were used, Figure 7. All flexible water connections on this tooling, including the torch coolant lines, were constructed from convoluted stainless steel tubing providing essentially zero moisture permeability. Integrally spined copper tubing was used in the heat exchanger providing excellent heat transfer characteristics. The installed exchanger was baffled and canted in a manner which enhances convection. The heat exchanger provided a comfortable chamber atmosphere temperature. The water-cooled platen and torch maintained adequately low temperatures in the work area for operator comfort and to avoid overheating, evaporation, or decomposition of gloves and torch insulators. The torch is equipped with a radiation shield. The use of a shield has proven to be a necessity because of the increased thermal radiation of the high melting point refractory metal alloys.

Welding procedures for the different alloys were generally the same. Tungsten arc, direct current straight polarity, manual welding was used. All specimens were prepared with the same double "U" joint configuration. The joint design and typical weld macrosections are shown in Figure 8. This is not necessarily an optimized design but proved satisfactory for all the alloys investigated. The root of the welds were tacked together with zero joint clearance, and the fusion root pass was made without the addition of filler metal. Additional passes, two for the columbium base alloys and two or three for the tantalum base alloys, on each side with filler wire added manually completed the butt weld. Filler wire of the same composition as the base metal was used. The filler wire diameter was 0.082 inch. Weldment flatness was controlled by alternate welding on opposite sides of the weld joint, and by introducing a camber into the joint (by adjusting a tack weld holding fixture) before applying the root pass. These actions taken at the discretion of an experienced welder proved adequate for flatness control. Amperage and welding speed were both controlled by the welder. These were approximately the same for a particular alloy group. Support blocks of either columbium or tantalum were placed under the specimens during welding to avert contact with and, hence, pickup of copper from the water-cooled work platen.

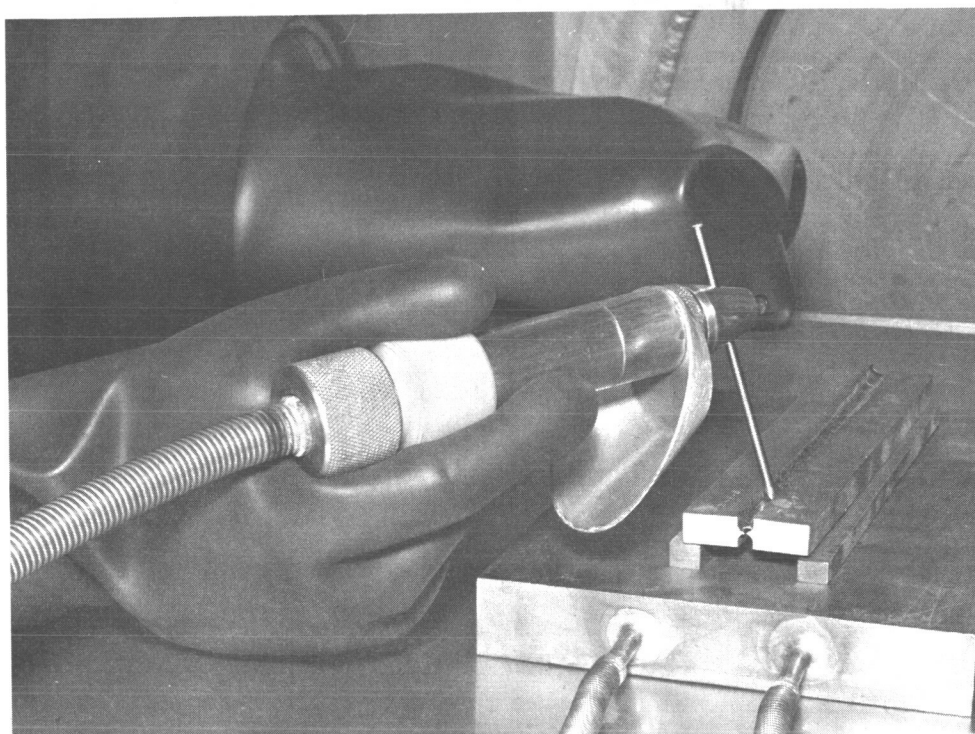
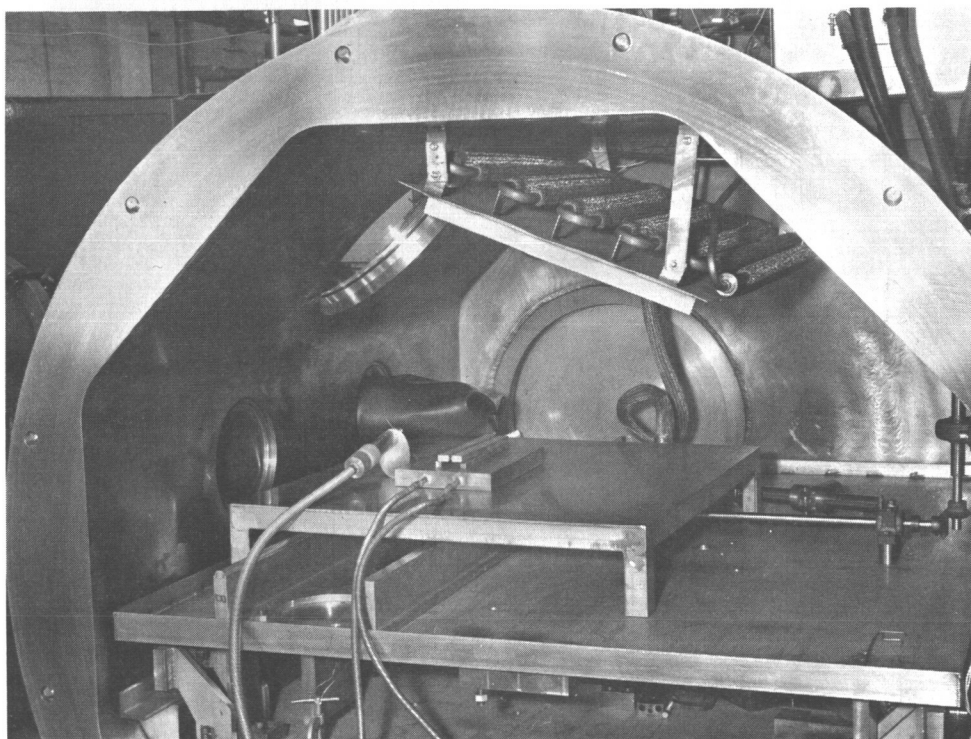


FIGURE 7 - Torch and Internal Chamber Arrangement for
Manual Plate Welding

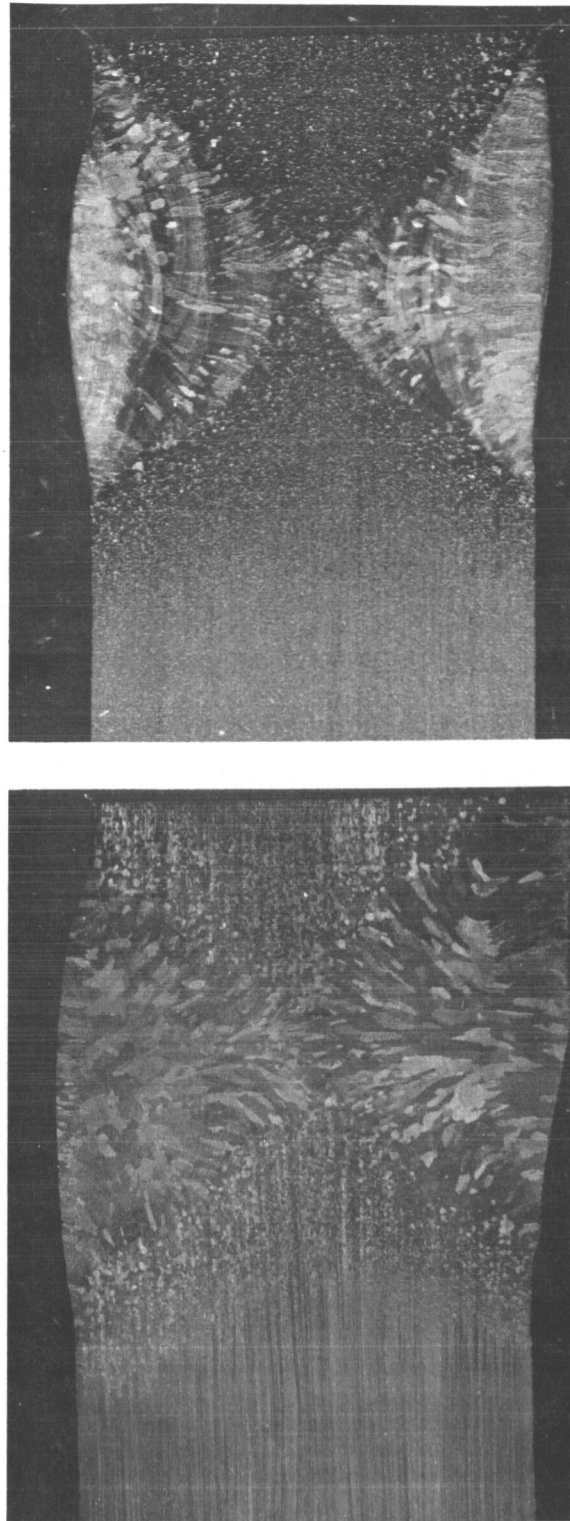
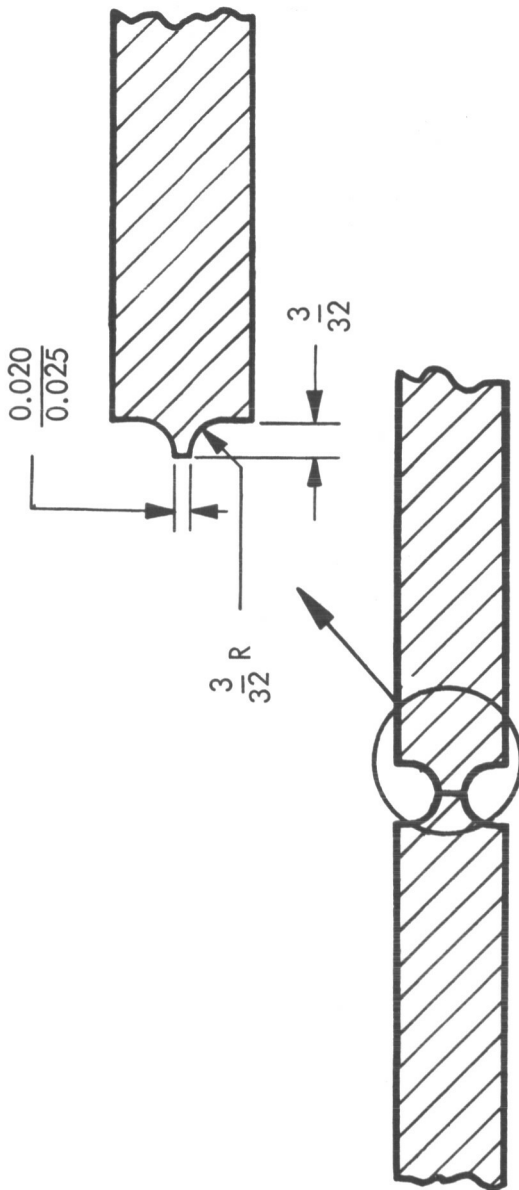


FIGURE 8 - Plate Butt Weld Joint Designs and Typical Macrosections

PLATE BEND TESTING

All plate weld bend testing was done at room temperature using single point loading over a fixed test span. Each specimen was tested in three stages using successively sharper punch radii. The three punches used have radii of $16t$, $8t$ and $3t$. These are used to produce successive respective bend angles of approximately 25° , 40° , and 140° , and calculated outer fibre tensile strains of 3%, 6%, and 14%. Bend specimens were of conventional size, $1\frac{1}{2}$ inches wide by 6 inches long. Welds were tested without any mechanical surface preparation, i. e. as-welded. The bend test fixture and examples of bend-tested weldments are shown in Figure 9.

TENSILE TESTING

Tensile testing was conducted according to recommended Material Advisory Board procedures.³ For room temperature tensiles a strain rate of 0.005 in/in/min was used through the 0.6% offset yield point, then 0.05 in/in/min to specimen fracture. The 0.05 in/in/min strain rate is used throughout the test at elevated temperatures. Room temperature tensiles had two-inch gage lengths except for longitudinal plate welds which had $1\frac{1}{2}$ inch gage lengths. Elevated temperature tensile specimens had one inch gage lengths. The gage section of sheet tensiles was 0.250 inch wide with an as-rolled finish for base metal samples, and ground parallel surfaces for weld specimens. All plate specimens had machined gage sections of 0.179 inch diameter or approximately 0.025 square inch cross sectional area.

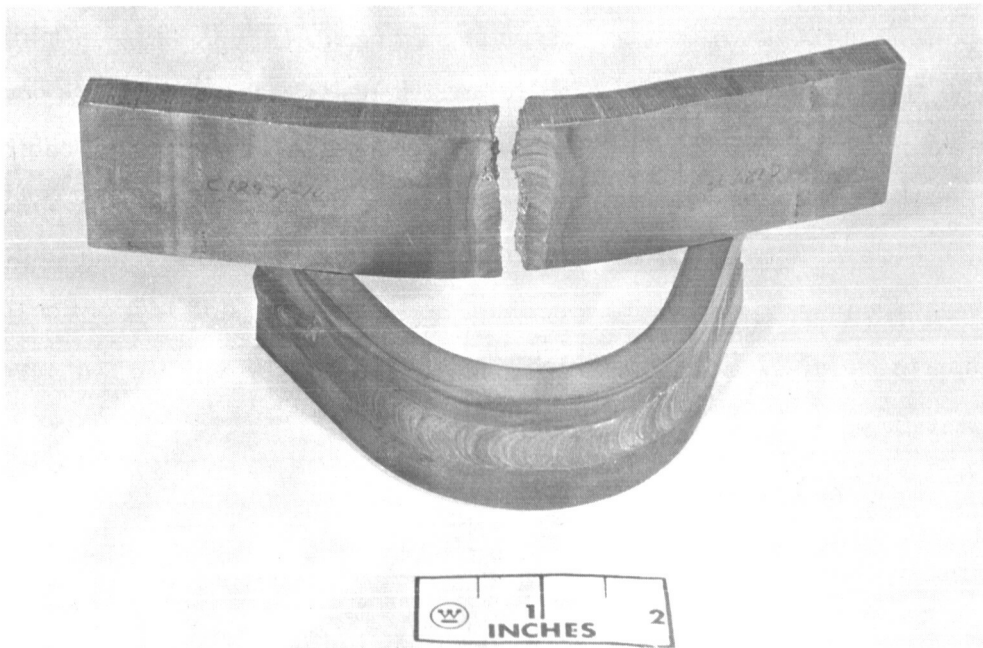
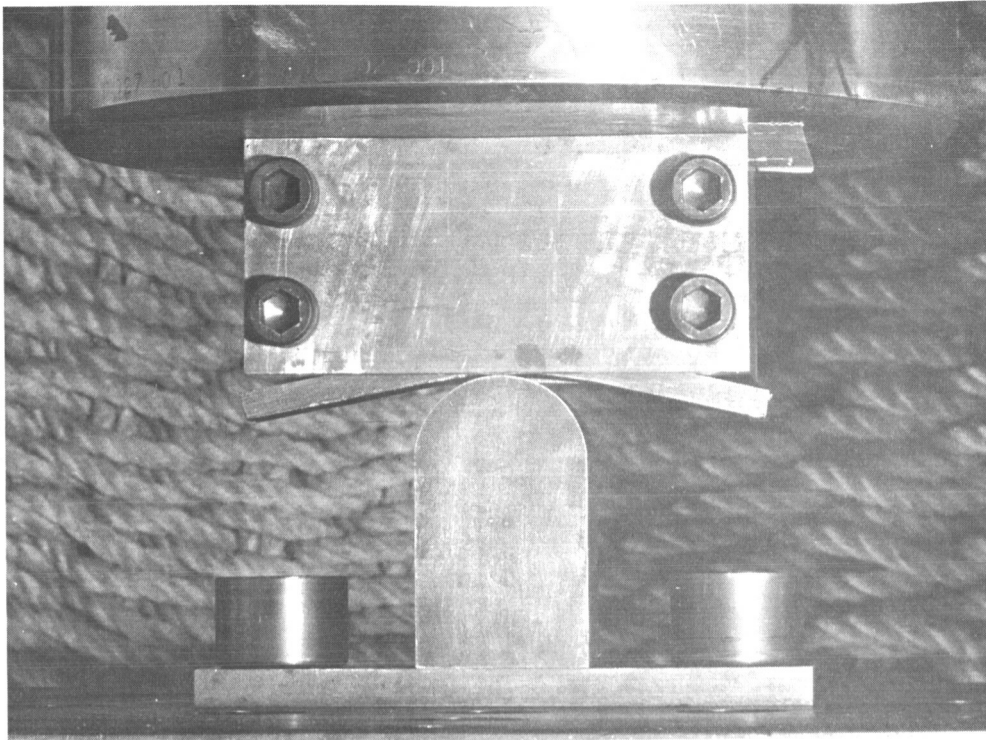


FIGURE 9 - Plate Bend Test Fixture and Typical Bend Tested Weldments

RESULTS

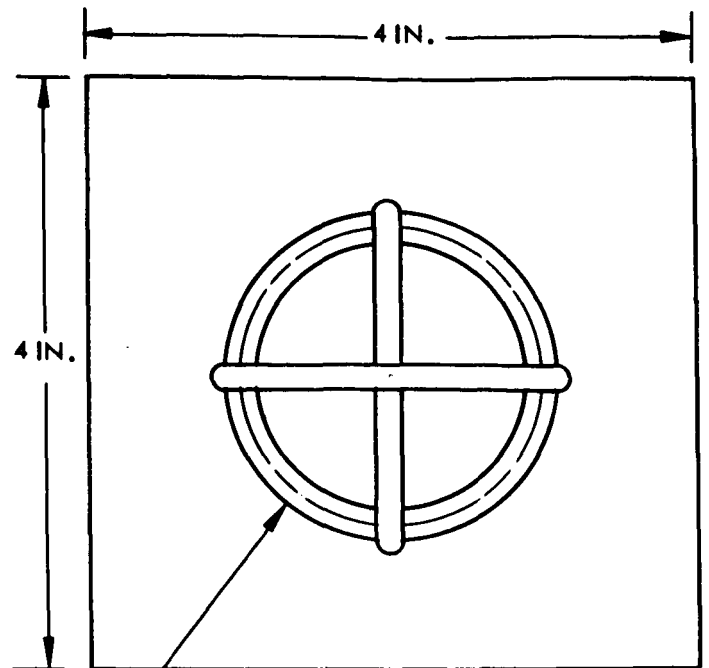
RESTRAINT TESTS

The first welds made were manually welded restraint tests. These tests are convenient for screening alloys for hot tear sensitivity and are useful in demonstrating simple weldability as measured by the ability to produce sound welds using conventional welding practice.

Sketches of the specimens employed in these tests are shown in Figure 10. Sheet and plate specimens were inspected visually and by dye penetrant tests. Sheet specimens were also radiographed and a summary of all test results is presented in Table 2. A measure of the relative strain introduced in these tests is provided by the distortion measurements listed in this table. Considerable distortion occurred in all specimens indicating the severity of these tests. Because of experimental variability, as noted particularly by differences in weld width, the distortion per se is probably not a valid basis for alloy comparison. Also, distortion is routinely encountered and accommodated in welding fabrication.

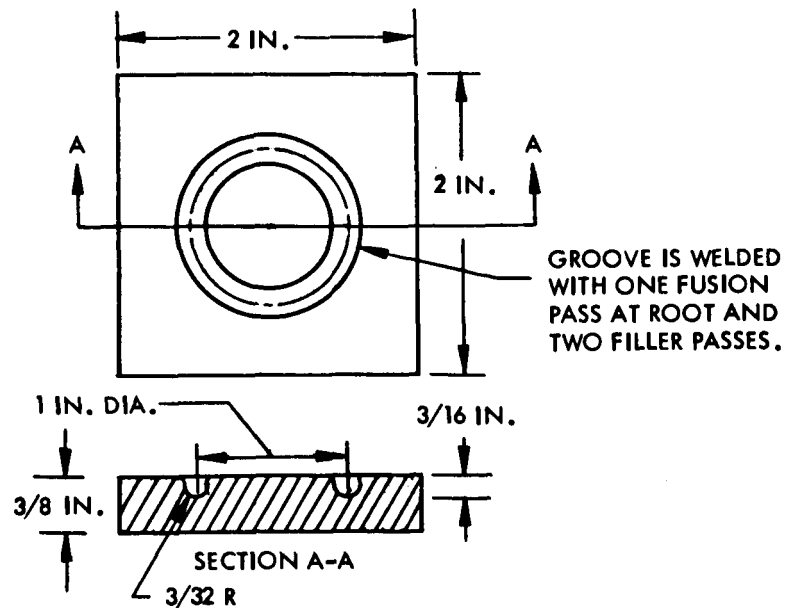
All patch tests showed NDT indications at weld craters but these were not listed as "positive" in Table 2 since they could have been eliminated by weld current tailing. The B-66 patch test had a positive indication of a 1/8 inch weld start crack by both radiographic and dye-penetrant testing. This crack is probably a hot tear since this problem has been previously observed in welding B-66. Positive indications in FS-85 radiographs were traced to weld texture, not defects.

No defects were detected in the circular groove plate weld specimens. These specimens were welded with a fusion root pass to increase the effective weld depth. Two filler passes were required to fill the groove. Filler was manually added to the weld using 0.082 inch diameter wire of the same composition as the base material. As with the patch tests, no particular difficulty was encountered and all alloys appear to have satisfactory weldability.



2 IN. DIAMETER CIRCLE AND CROSS WELDED
IN SHEET. NO FILLER WIRE USED.

(A) BEAD-ON-PLATE RESTRAINT PATCH TEST DESIGN



(B) CIRCULAR GROOVE WELD RESTRAINT TEST SPECIMEN

603897-3 B

FIGURE 10 - Weld Restraint Test Specimens for 0.035 Inch Sheet
(a), and 0.375 Inch Plate (b).

TABLE 2 - Restraint Test Summary

Alloy	Bead-on-Plate Patch Test (Sheet)					Circular Groove (Plate)		
	Visual	Weld Width	Dye Check	X-ray	Distortion		Visual	Dye Check
					Angle (Max)	Inches ¹		
AS-55	Neg.	0.24	Neg.	Negative	13°	0.75	(5)	---
B-66	Neg.	0.23	Neg.	Positive ³	31°	0.63	Neg.	Neg.
C-129Y	Neg.		Neg.	Negative	30°	0.63	Neg.	Neg.
Cb-752	Neg.	0.34	Neg.	Negative	28°	0.73	Neg.	Neg.
D-43	Neg.	0.23	Neg.	Negative	32°	0.60	Neg.	Neg.
D-43Y	Neg.	0.11	Neg.	Neg.	25°	0.70	(5)	---
FS-85	Neg.	0.15	Neg.	Positive ⁴	36°	0.76	Neg.	Neg.
SCb-291	Neg.	0.20	Neg.	Negative	32°	0.69	Neg.	Neg.
Ta-10W	Neg.	0.17	Neg.	Negative	30°	0.70	Neg.	Neg.
T-111	Neg.	0.22	Neg.	Negative	26°	0.60	Neg.	Neg.
T-222	Neg.	0.25	Neg.	Negative	18°	0.65	Neg.	Neg.

1. Closest distance between two parallel planes on opposite sides of weldment.
2. Holding one corner flat, measure lift from flat plane at diagonally opposite corner.
3. 1/8 inch starting crack identified on one leg of weld.
4. Positive x-ray indication not identified in consequent examination.
5. This alloy not evaluated as plate.

WELD PARAMETER STUDY

Using the procedures and approach previously described, the alloys were evaluated with respect to their response to weld parameter variation. Bend ductility, as measured by the bend ductile-brittle transition temperature, (DBTT), was used to measure the effect of weld variables. This study was restricted to welding 0.035 inch sheet. Both TIG and EB welding were evaluated. Twelve welding conditions were used for each process in studying each alloy. Eight columbium and three tantalum based alloys were evaluated. Among the tungsten alloys, the electron beam study of W-25Re has been completed and is also reported.

A summary of the weld parameter study is shown in Figure 11. This figure shows the range, or total spread, in bend transition temperatures obtained in the weld parameter study for each alloy and process. Results of both longitudinal and transverse bend testing make up this summary since every weld was evaluated in both directions. Approximately 580 bend transition curves, requiring 2300 bend tests, were generated in this study. A detailed presentation of this data is too extensive for inclusion in this report.

The superior weldability of the tantalum alloys is even better than is implied by the summary in Figure 11 since the few failures in the tantalum alloys were generally ductile tears occurring at or near the 90 degree target bend angle. Columbium alloys, on the other hand, generally exhibited full section, low strain cleavage fractures at the ductile-brittle transition temperature. However, whether cleavage or ductile tearing, the DBTT was identified as the lowest temperature where no defects were detected. Hence, the DBTT identified for the tantalum alloys were frequently not "true" transitions but rather the temperature at which a strain limitation for ductile tearing was exceeded.

In electron beam welding, most alloys were structurally defected by at least one set of welding conditions. This is a result of the severity of this welding process wherein a high density beam provides penetration by evaporation as well as simple melting and at some power-speed-deflection combinations rough, rippled weld surfaces resulted. B-66 proved difficult to weld

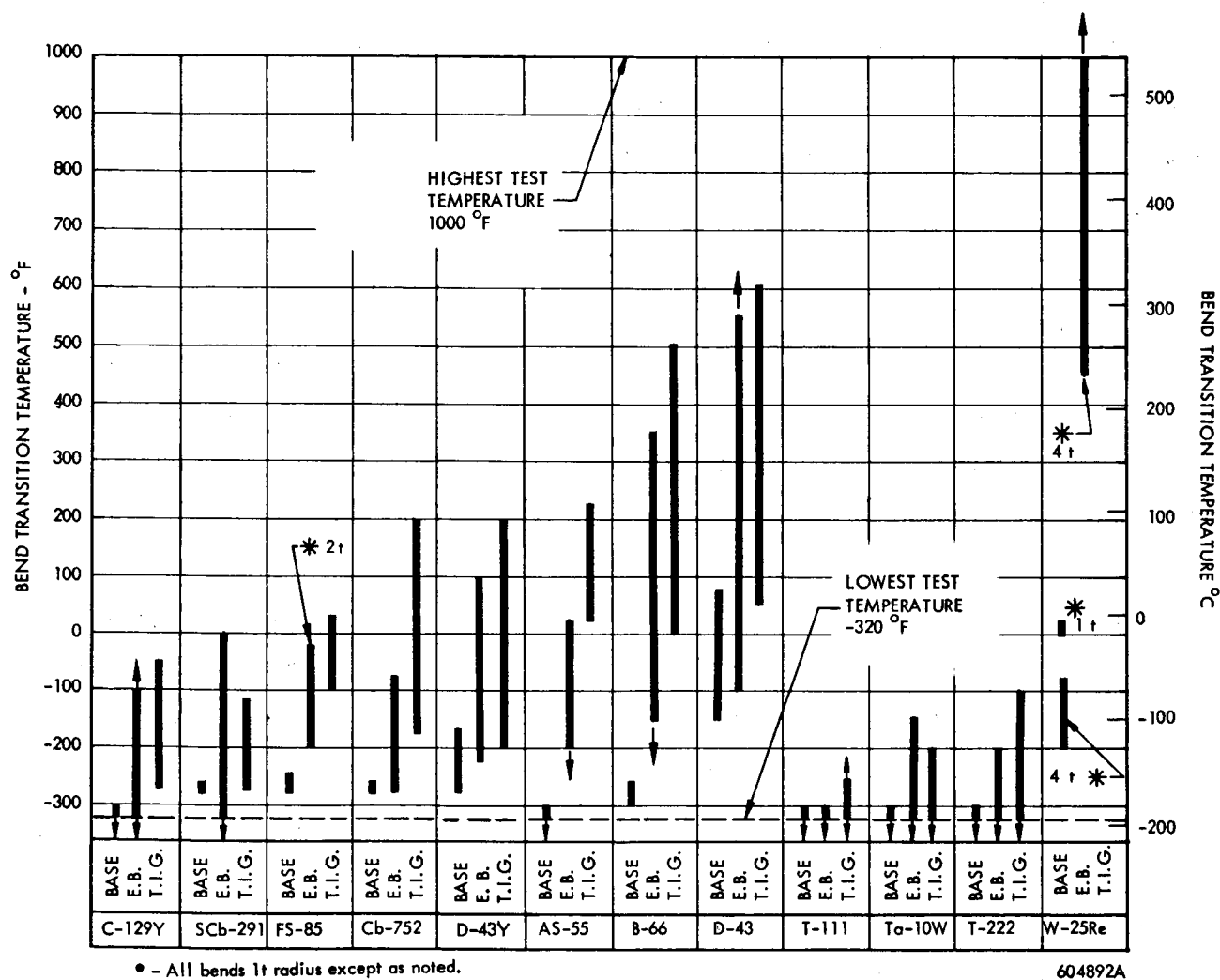


FIGURE 11 - Summary of Current Bend Test Results for
Butt Welds in 0.035 Inch Sheet

in this respect in that 7 of 12 welds rippled. This effect is probably related to the vapor pressures of the various alloy constituents. The most unusual and, hence, the suspect alloy addition in B-66 is vanadium. EB welds were carefully examined for structural soundness and bend test results were scrutinized to determine if physical structure prejudiced the bend test results. This seemed to be the case for B-66 and D-43 both of which would have an upper transition temperature limit 200 or 300 degrees lower than shown in Figure 11 if visually defective welds were not considered. Their relative position on this chart would, however, not be changed.

The only process limitations associated with TIG welding occurred at the highest welding speed, 60 inches per minute. At this speed micro-fissures occurred in B-66 and weld center-line shrinkage voids were observed in C-129Y. Again, the effect of these defects on the bend transition temperature did not change the relative ductility rating of these alloys as indicated in the bend test summary.

Several alloys displayed slightly improved TIG weld ductility with increased weld speed, narrower clamp spacing, and smaller welds. Moderate welding speeds and longitudinal beam deflection gave the most uniform EB welds and also favored improved ductility. By in large, however, a careful examination of all the fractured bend specimens and test results failed to reveal significant trends relating weld parameters to bend ductility. This is an interesting result in itself, since one can infer that the absolute value and spread in ductility observed are innate alloy characteristics rather than a measure of the effect of welding variables. In this respect, Figure 11, which compares the alloys on the basis of total spread in bend transition temperature provides a comparison of an actual alloy characteristic, the variability of weld ductility. Hence, alloys can be compared using this data both on the basis of the lowest transition temperature obtainable and the variability involved in obtaining a desired degree of ductility.

Among the columbium alloys, C-129Y had the lowest weld transition temperatures. The yttrium addition in this alloy is apparently instrumental in obtaining this improved ductility.

Likewise, D-43Y is considerably more ductile than D-43, and AS-55 which contains yttrium, displays good ductility considering the fact that it contains more than three times the oxygen (600+ ppm) than the other alloys. Oxygen contamination, particularly at this level, usually causes extreme impairment of ductility in columbium alloys. Yttrium containing alloys, however, displayed peculiarities which cause moderate concern over their applications in liquid metal systems. D43Y showed a tendency to hot tear in TIG butt welding. This may have been a geometric effect since narrow strips were used. Several AS55 bend specimens fractured down the weld centerline along what appeared to be a largely continuous plane of weakness, and one weld in C129Y tore along the weld centerline during welding. The C129Y tear was easily extended by hand tearing. Other investigators have observed an apparent migration of yttrium oxide in alkali metal loops. ⁽⁴⁾

FS-85 had the narrowest transition temperature range among the columbium alloys and, hence, provides the most consistent ductility. This would be an important advantage in most applications. The solid solution strengthened alloy SCb-291 also had good as-welded ductility. All the tantalum alloys had excellent ductility, while W-25Re, the first of the tungsten alloys evaluated, proved to be very poor in this respect.

POST WELD ANNEALING STUDY

The effect of post weld annealing on the weld ductility of the various alloys is shown for TIG welds in Figure 12 and for EB welds in Figure 13. Approximately 120 bend transition curves are summarized in these figures. This comparison of alloy behavior is based on longitudinal bend transition temperatures. Similar results were obtained for transverse bend testing and are therefore not shown. Broken curves are shown below the lowest annealing temperatures since annealing response in this range was not determined.

The one hour post weld annealing temperatures were selected in the stress relief-recrystallization range. Hence, the columbium alloys were annealed at 1900°F, 2200°F, and 2400°F, while the tantalum alloys were annealed at 2400°F, 2700°F, and 3000°F. Welding parameters which produced the lowest DBTT, as determined in the weld parameter study, were used in preparing welds for this evaluation. The selected weld parameters are listed in Table 3 along with the most beneficial post weld anneals identified in this study.

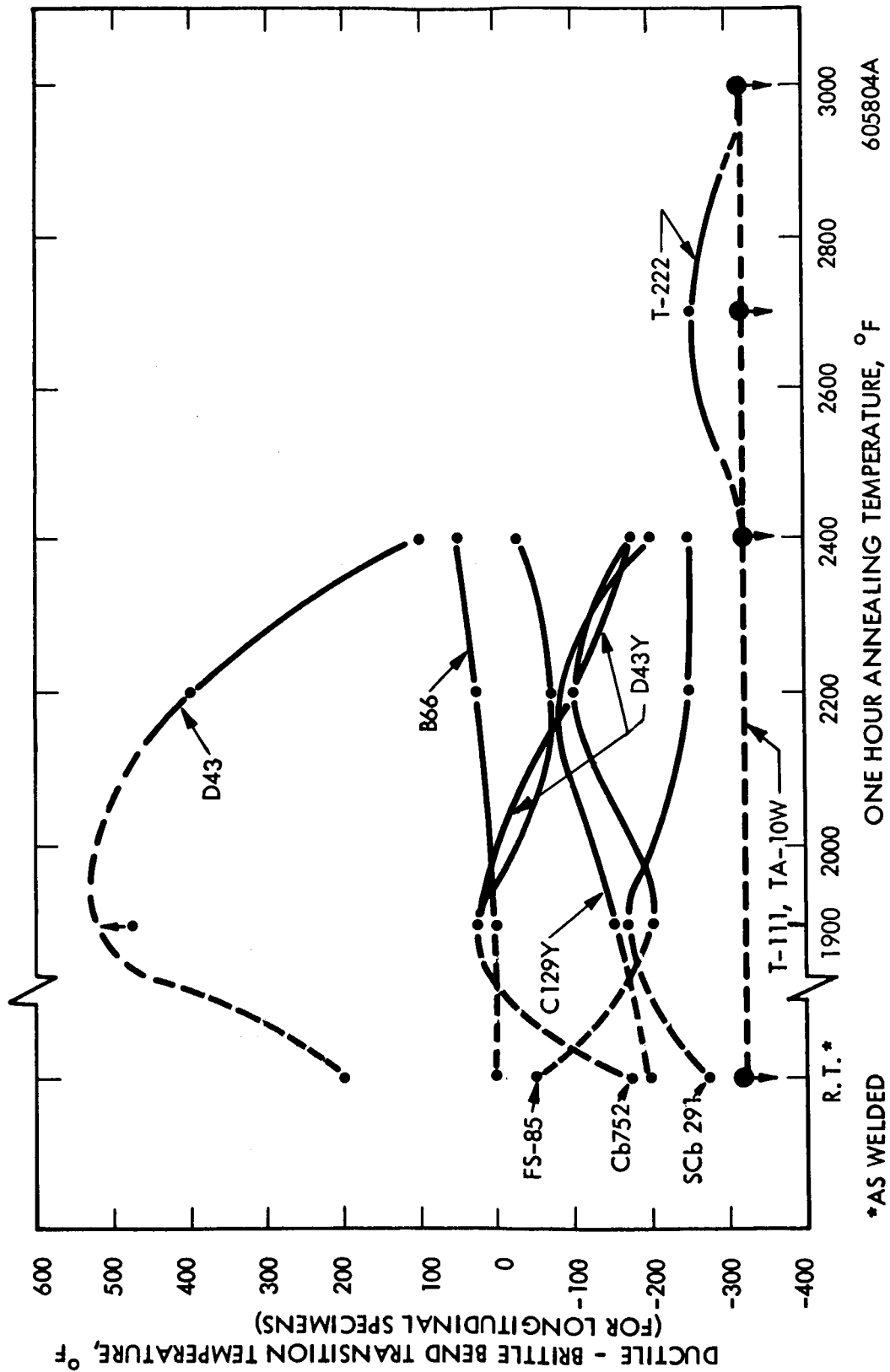


FIGURE 12 - Summary Showing the Effect of Annealing on TIG Weld Bend Ductility

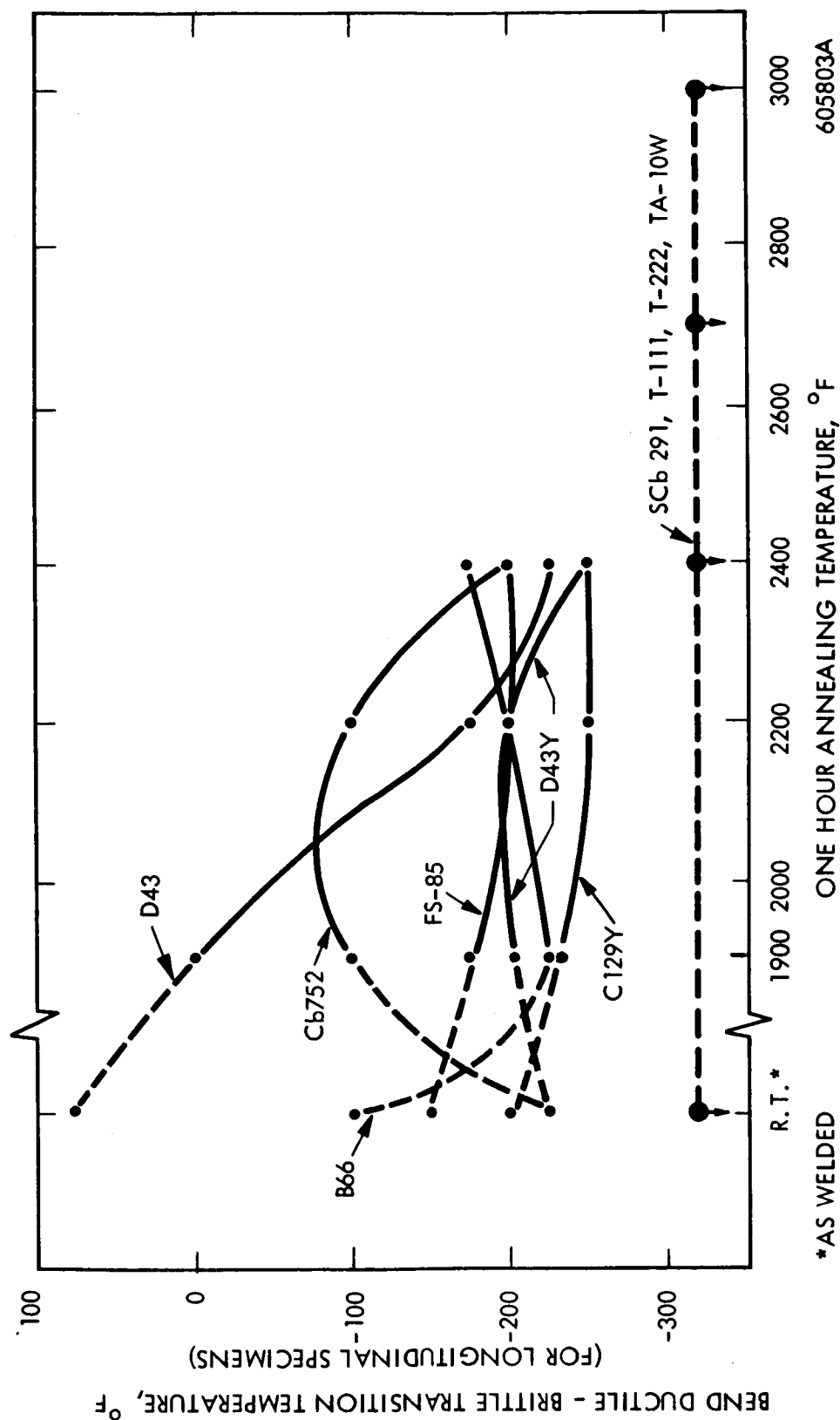


FIGURE 13 - Summary Showing the Effect of Annealing on EB Weld Bend Ductility

Measurable responses to post weld annealing were noted for all the columbium alloys. TIG welds in D-43, Cb-752, C-129Y and SCb-291 appear to experience an age-overage** response with increasing annealing temperature. All these tend to lose ductility at the lower annealing temperatures and recover at the higher temperature. D-43 demonstrated the most severe aging response. Interestingly, the yttrium modified material, D-43Y, merely improved in ductility with increased annealing temperature to the extent of nearly recovering base metal ductility after one hour at 2400°F. FS-85 TIG welds had a double aging response improving in ductility at 1900°F, aging at 2200°F and averaging at 2400°F. A similar response for FS-85 welds was previously observed.⁽⁵⁾ B-66 TIG welds showed a 50°F increase in the DBTT which probably resulted primarily from grain growth. TIG welded tantalum alloys, except T-222 annealed at 2700°F, did not respond to aging with any apparent change in ductility.

Electron beam welds in columbium alloys did not generally display the age-average response characteristic of the TIG welds. In this group, Figure 13, only Cb-752 had a marked age-average response while D-43Y had a slight aging response. The other columbium alloys have improved annealed weld ductility while the tantalum alloys and SCb-291 EB welds were ductile below -320°F for all conditions.

TENSILE TEST RESULTS

Tensile test results for 0.035-inch sheet base metal and transverse welds are summarized in Figures 14, 15, and 16. All alloys were tested at room temperature and 1800°F, 2100°F, and 2400°F. Both base and weld specimens were annealed using the optimum conditions identified for each alloy in the post weld annealing study. Optimum weld parameters were used for preparing the TIG weld specimens. The welding parameters and annealing temperatures used are listed in Table 3.

The tantalum alloys are generally stronger than the columbium alloys, particularly at the higher temperature. The solid solution strengthened alloys, Ta-10W and SCb-291, are noticeably weaker in their respective alloy groups. This demonstrates the beneficial effect realized from the reactive element solute additions (Zr and Hf) in columbium and tantalum alloys. D-43 has the highest strength among the columbium alloys and displays a weld strength equivalent to base metal strength. D-43Y is significantly weaker than D-43 and superior only to

**NOTE: In this discussion "aging response" is a measured change in ductility. Where age-overage responses occur, one would infer a precipitation aging reaction.

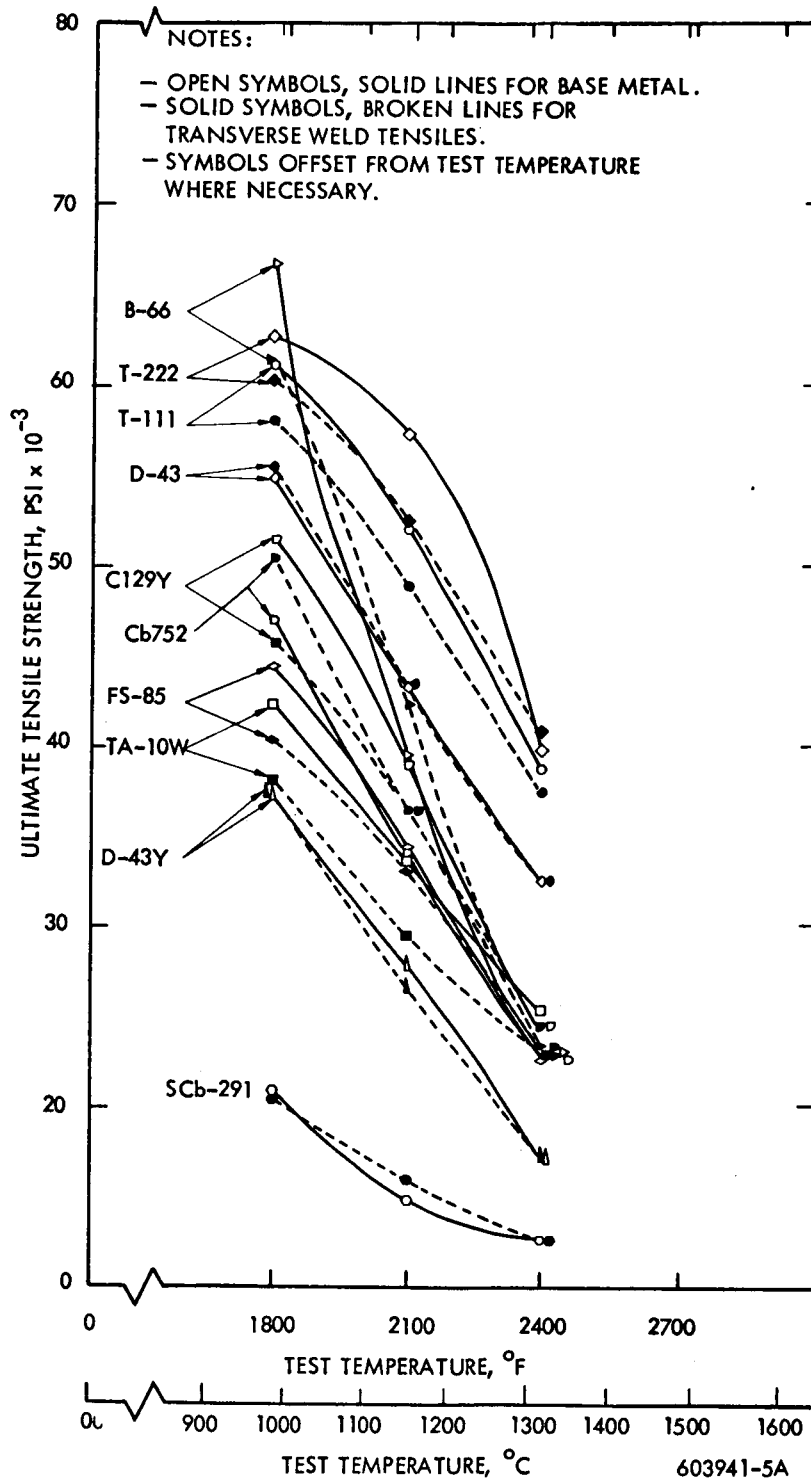


FIGURE 14 - Elevated Temperature Tensile Strength of Annealed Base Metal and TIG Welds. Optimum Welding and Annealing Schedules Used, See Table 3.

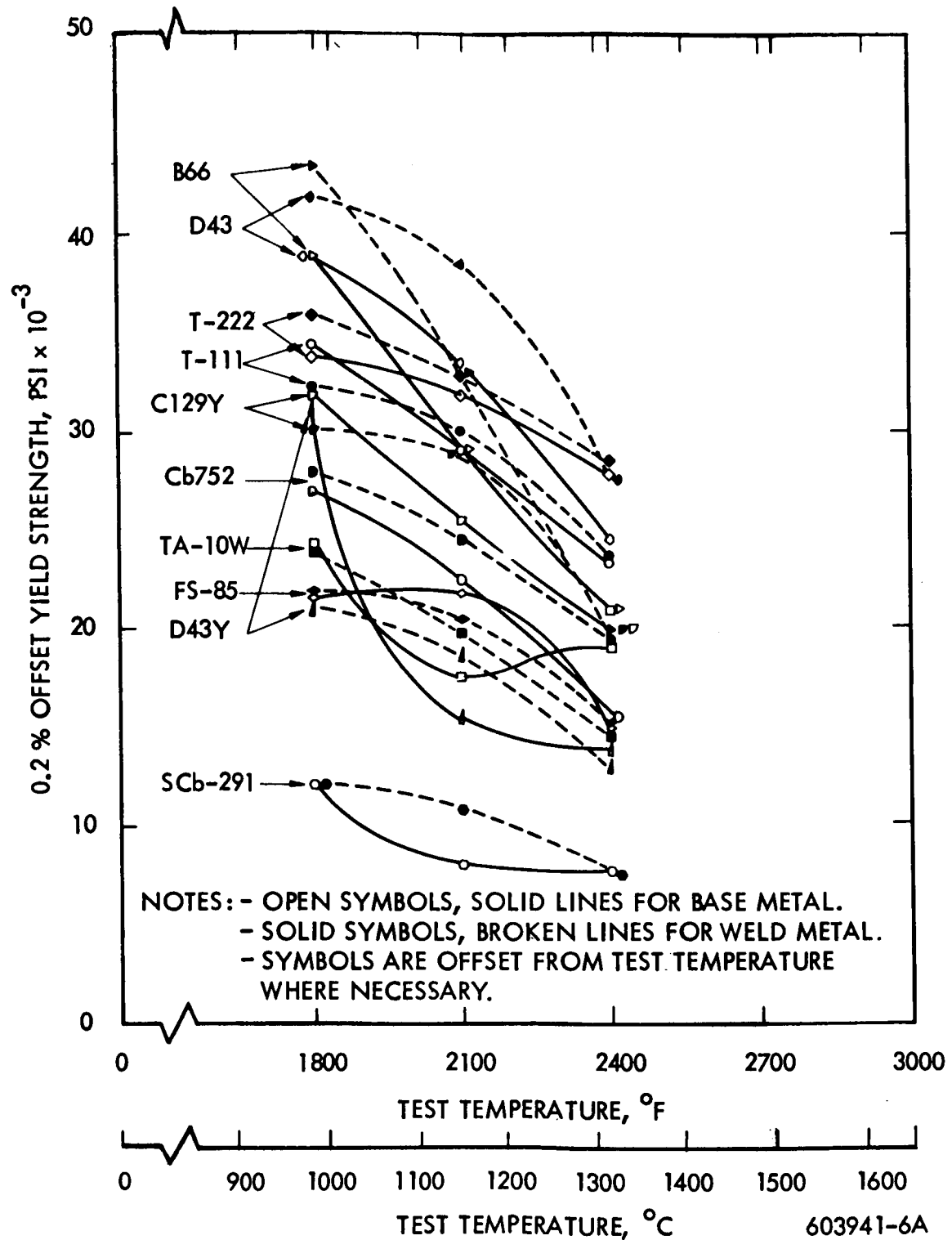


FIGURE 15 - Elevated Temperature Yield Strength of Annealed Base Metal and TIG Welds. Optimum Welding and Annealing Schedules Used, See Table 3.

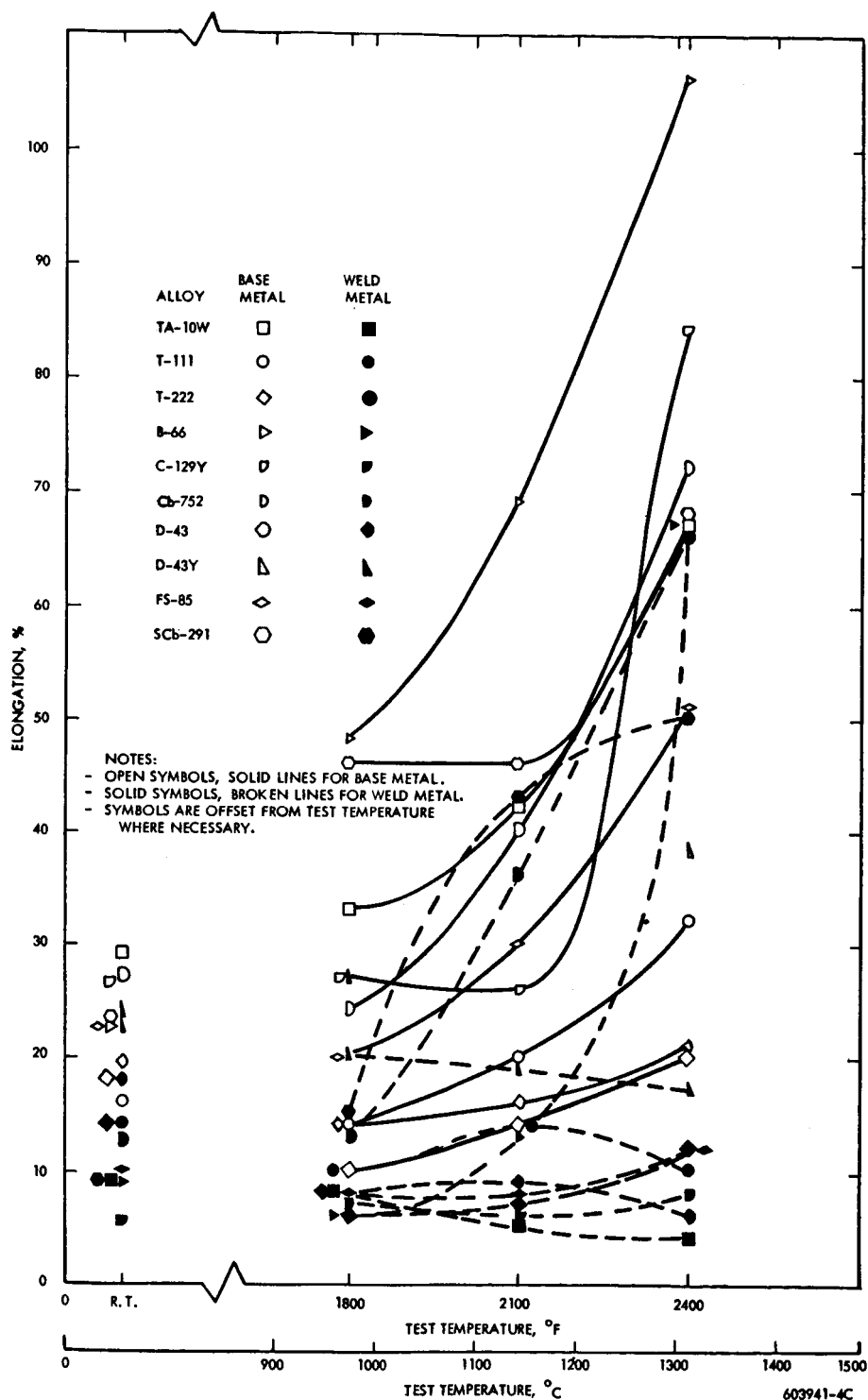


FIGURE 16 - Elevated Temperature Tensile Elongation of Annealed Base Metal and TIG Welds. Optimum Welding and Annealing Schedules Used, See Table 3.

TABLE 3 - Optimized Weld Conditions for 0.035 Inch Sheet

Alloy	Process	Parameters (1)	One Hour Post Weld Anneal Temp. , °F	Weld Width Top/Bottom (inches)	BDBTT, °F ⁽²⁾	
					Long. Bends	Trans. Bends
Ta-10W	TIG	7.5-1/4-118	None	.190/.180	<-320	<-320
	EB	15-1/2-4.5	None	.049/.034	<-320	<-320
T-111	TIG	15-3/8-115	2400°F	.195/.189	<-320	<-320
	EB	15-1/2-3.8	2400°F	.038/.027	<-320	<-320
T-222	TIG	30-1/4-190	2400°F	.180/.159	<-320	<-320
	EB	15-1/2-3.8	2400°F	.039/.026	<-320	<-320
B-66	TIG	15-3/8-86	None	.190/.180	0	+75
	EB	25-3/16-3.2	1900°F	.036/.024	-225	-175
C-129Y	TIG	30-3/8-110	2400°F	.180/.130	-200	-225
	EB	50-1/2-4.1	2200°F	.040/.026	-250	-250
Cb-752	TIG	30-3/8-87	2200°F	.129/.090	-75	0
	EB	15-3/16-3.3	2400°F	.036/.017	-200	-200
D-43	TIG	30-3/8-114	2400°F	.159/.143	+100	0 ⁽³⁾
	EB	50-1/2-4.4	2400°F	.040/.027	-225	-225
D-43Y	TIG	15-3/8-83	2400°F	.165/.150	-175	-250
	EB	50-1/2-4.0	2400°F	.036/.022	-250	<-300
FS-85	TIG	15-3/8-90	2400°F	.204/.195	-175	-175
	EB	50-3/16-4.4	2200°F	.038/.026	-200	-200
SCb-291	TIG	15-1/4-83	2200°F	.160/.150	-275	-275
	EB	50-1/2-4.4	None	.038/.027	<-320	-250

- (1) For TIG Welds: Speed (ipm) - Clamp Spacing (in.) - Amperes
 For EB Welds: Speed (ipm) - Clamp Spacing (in.) - Milliamperes
 (All EB welds with 60~, 0.050 inch longitudinal deflection and
 150 KV beam voltage)

- (2) BDBTT ≈ Bend Ductile Brittle Transition Temperature at 1t Bend Radius Except
 FS-85 EB Welds at 2t Bend Radius.

- (3) Probable Value (Determined Value <-125°F)

SCb-291. At 2400°F most of the columbium alloys display about the same strength level with only D-43 being stronger, and D-43Y and SCb-291 being weaker. The tantalum alloy advantage over columbium alloys, based on density uncorrected tensile strength, occurs above 2000°F.

Joint efficiencies for the alloys approach 100 percent at all test temperatures. Both base metal and weld metal have good ductility. Low total elongations are noted for some transverse welds, but fractures were characterized by localized straining and high reductions in area.

PLATE WELDING

The plate butt welding evaluation was included in this program to ascertain the effect of section thicknesses on weldability. In general, weldability requirements tend to become more stringent with increased section thickness and the effect of welding on mechanical properties becomes exaggerated. Hence, the plate weld evaluation represents an important phase of this program complementing the sheet weld study.

Because of the large size of plate weldments, and thus high material cost, the scope of this effort was more restricted than for the sheet weld evaluation. Nine alloys were included in the plate welding study. These included all the columbium and tantalum alloys except D43Y and AS55. Approximately thirty-six feet of plate welding was required for this phase. Plates were welded manually by two different weld operators and evaluated primarily by bend and tensile testing in both the longitudinal and transverse directions. One post weld anneal for each alloy was also selected, based on sheet welding results. All of the alloys were successfully joined using the procedures described earlier in this report. B-66 was difficult to weld because of a hot tearing tendency which was overcome only by applying strong tack welds at each end of the weldments before making the rest of the weld.

The room temperature tensile test results are summarized in Table 4. Tensile tests were run only on annealed weld specimens. To obtain a measure of the joint efficiencies of the plate



TABLE 4 - Room Temperature Tensile Properties for Welded Plate

Alloy	Type	1 Hr. Post Weld Anneal Temp. (°F)	0.2% Offset Yield Pt. $\times 10^{-3}$ psi	Ultimate Stress $\times 10^{-3}$ psi	R. A. (%)	Elongation (%)	Fracture Location
T-111	Trans.	2400	73.70	86.99	76.0	17.4	Weld
T-111	Long.	2400	76.20	89.85	64.7	22.3	--
Ta-10W	Trans.	None	61.16	77.71	82.2	21.9	Weld
Ta-10W	Long.	None	65.85	81.30	70.0	24.3	--
T-222	Trans.	2400	88.21	101.01	74.4	18.7	Weld
T-222	Long.	2400	87.99	100.74	68.3	21.9	--
B-66	Trans.	1900	(1)	68.36	0.0	0.0	Weld
B-66	Long.	1900	77.79	88.81	2.6	6.6	--
D-43	Trans.	2400	59.40	79.74	70.7	5.2	Weld
D-43	Long.	2400	54.86	88.22	28.7	17.4	--
FS-85	Trans.	2400	60.21	76.72	9.7	9.4	Weld
FS-85	Long.	2400	61.81	79.82	66.6	21.0	--
Cb-752	Trans.	2200	56.32	75.90	79.7	24.9	Base
Cb-752	Long.	2200	61.00	79.30	46.2	20.7	--
SCb-291	Trans.	1900	47.03	62.70	88.9	22.5	Weld
SCb-291	Long.	1900	46.86	62.47	77.5	21.2	--
C-129Y	Trans.	2400	70.07	87.38	16.9	12.7	Weld
C-129Y	Long.	2400	68.10	86.90	44.7	22.0	--

(1) Brittle Fracture

welds, a comparison of welded plate and sheet tensile strength is shown in Figure 17. This figure shows that the tensile joint efficiency of most of the alloys is approximately 100 percent. Interestingly, there is not much alloy to alloy variability in room temperature strength. This probably reflects a fabricability limitation since increased room temperature strength is usually achieved with a corresponding decrease in fabricability.

Bend test results for these alloys are listed in Table 5. The variability in weld ductility corresponds very nearly with the results obtained in sheet welding. A brief summary of test results on welded plate is given below for each alloy. The alloys are discussed in order of decreasing ductility. The tantalum alloys are all superior to the columbium alloys in this respect and are therefore discussed first.

Ta-10W. This alloy has excellent as-welded ductility in plate and sheet thickness as demonstrated in tensile and bend tests. Its performance was the best among the alloys tested. The as-welded longitudinal plate tensile test had an elongation at 24%, easily sufficient to accommodate the highest strain requirements of the 3t bend test. Ta-10W was not tested in the post-weld annealed condition since there is no apparent benefit to be gained by annealing. Comparing the plate weld tensiles to sheet base tensiles, a joint efficiency of greater than 90% can be assumed.

T-111 - This alloy had slightly lower ductility than Ta-10W as evidenced by slight surface weld tearing. No defects were noted in annealed specimens. The annealed longitudinal plate weld tensile specimens had excellent ductility with 22% elongation. Metallography revealed slight weld grain boundary precipitation and also a heat affected zone-base metal interface precipitate which was previously observed in sheet welds and identified as hafnium monocarbide. The tensile joint efficiency for T-111 appears to be about 100%.

TABLE 5 - Welded Plate Bend Test Results

Alloy	Specimen No.	Type	Condition ⁽¹⁾	1st Bend, 16 t Bend Rad.		2nd Bend, 8t Bend Rad.		3rd Bend, 3t Bend Rad.	
				Free Bend Angle (2)	Proportional Limit, Psi	Free Bend Angle (2)	Proportional Limit, Psi	Free Bend Angle (2)	Proportional Limit, Psi
B-66	1-2	Long.	AW	4°	N.D.	- - -	- - -	- - -	- - -
	5-6	Long.	AW	0°	66,950	- - -	- - -	- - -	- - -
	7-8	Long.	PWA 1 hr/1900°F	17°	99,730	50°	107,140	67°	108,560
	9-10	Trans.	AW	4°	N.D.	- - -	- - -	- - -	- - -
	11-12	Trans.	AW	22°	103,090	37°	119,960	- - -	- - -
	13-14	Trans.	PWA 1 hr/1900°F	0°	76,580	- - -	- - -	- - -	- - -
C129Y	1-2	Long.	AW	25°	N.D.	49°	133,740	132°	128,950
	3-4	Long.	AW	22°	90,540	60°	110,390	135°	103,420
	7-8	Long.	PWA 1 hr/2400°F	17°	95,520	40°	95,060	137°	97,620
	9-10	Trans.	AW	22°	N.D.	27°	147,490	- - -	- - -
	13-14	Trans.	AW	25°	79,100	60°	95,880	- - -	91,020
	11-12	Trans.	PWA 1 hr/2400°F	15°	88,840	50°	94,760	137°	88,170
Cb752	1-2	Long.	AW	29°	N.D.	- - -	- - -	- - -	- - -
	3-4	Long.	AW	0°	79,560	- - -	- - -	- - -	- - -
	7-8	Long.	PWA 1 hr/2200°F	22°	65,030	52°	74,320	- - -	- - -
	9-10	Trans.	AW	26°	N.D.	45°	90,490	- - -	- - -
	13-14	Trans.	AW	20°	81,360	62°	98,610	140°	79,960
	11-12	Trans.	PWA 1 hr/2200°F	20°	80,500	30°	83,930	- - -	- - -
D43	1-2	Long.	AW	23°	N.D.	39°	122,730	- - -	- - -
	3-4	Long.	AW	25°	97,220	60°	86,580	- - -	78,340
	5-6	Long.	PWA 1 hr/2400°F	17°	82,580	45°	82,540	130°	83,600
	9-10	Trans.	AW	23°	N.D.	36°	106,280	47°	105,770
	13-14	Trans.	AW	23°	75,200	60°	87,890	- - -	67,790
	11-12	Trans.	PWA 1 hr/2400°F	17°	71,780	35°	85,980	135°	87,450

(1) AW - As-welded, PWA - Post-Weld Annealed (Time-Hrs/Temp-°F Indicated).

(2) Letters B & F in this column designate "Bend" or "Failed" (any tear or crack) Respectively.

ND — Not determined.

TABLE 5 - Welded Plate Bend Test Results (Continued)

Alloy	Specimen No.	Type	Condition (1)	1st Bend, 16t Bend Rad.		2nd Bend, 8t Bend Rad.		3rd Bend, 3t Bend Rad.	
				Free Bend Angle (2)	Proportional Limit, Psi	Free Bend Angle (2)	Proportional Limit, Psi	Free Bend Angle (2)	Proportional Limit, Psi
FS-85	1-2	Long.	AW	27° B	N.D.	40° B	160,290	125° F	135,500
	3-4	Long.	AW	25° B	79,370	40° F	95,240	- - -	- - -
	7-8	Long.	PWA 1 hr/2400°F	17° B	86,100	60° B	85,390	145° B	83,600
	9-10	Trans.	AW	26° B	N.D.	40° B	124,030	145° B	119,600
	11-14	Trans.	AW	25° B	75,610	62° B	87,580	140° B	69,790
	12-13	Trans.	PWA 1 hr/2400°F	17° B	84,440	55° B	81,880	140° B	81,990
SCb-291	1-2	Long.	AW	23° B	N.D.	44° B	97,820	160° F	80,200
	3-4	Long.	AW	22° B	70,300	58° B	73,040	140° B	66,630
	7-8	Long.	PWA 1 hr/1900°F	20° B	68,060	62° B	67,180	140° B	62,930
	9-10	Trans.	AW	22° B	N.D.	37° B	87,810	132° B	94,920
	13-14	Trans.	AW	20° B	68,720	60° B	78,720	140° B	66,720
	11-12	Trans.	PWA 1 hr/1900°F	22° B	73,060	55° B	68,030	140° B	67,000
TA-10W	3-4	Long.	AW	29° B	N.D.	57° B	N.D.	141° B	N.D.
	5-6	Long.	AW	28° B	95,240	60° B	103,900	140° B	86,000
	9-10	Trans.	AW	28° B	N.D.	54° B	N.D.	141° B	N.D.
	11-12	Trans.	AW	28° B	98,550	60° B	103,880	140° B	97,630
T-111	1-2	Long	AW	27° B	94,590	62° B	102,680	142° B	87,350
	3-4	Long.	AW	27° B	101,630	62° B	109,600	142° F	99,960
	7-8	Long.	PWA 1 hr/2400°F	30° B	102,330	55° B	92,610	140° B	88,310
	9-11	Trans.	AW	20° B	95,490	55° B	118,060	142° B	105,070
	10-12	Trans.	AW	25° B	73,200	63° B	104,170	120° F	82,410
	13-14	Trans.	PWA 1 hr/2400°F	29° B	122,540	55° B	106,480	136° B	94,770
T-222	1-2	Long.	AW	25° B	139,360	60° B	148,640	142° F	126,380
	3-4	Long.	AW	25° B	116,610	60° B	137,800	142° F	125,800
	7-8	Long.	PWA 1 hr/2400°F	28° B	123,790	50° B	115,750	137° B	107,310
	9-10	Trans.	AW	25° B	120,870	60° B	140,640	140° F	114,000
	11-12	Trans.	AW	25° B	101,600	60° B	135,470	143° F	111,800
	13-14	Trans.	PWA 1 hr/2400°F	20° B	111,000	50° B	128,220	130° B	114,110

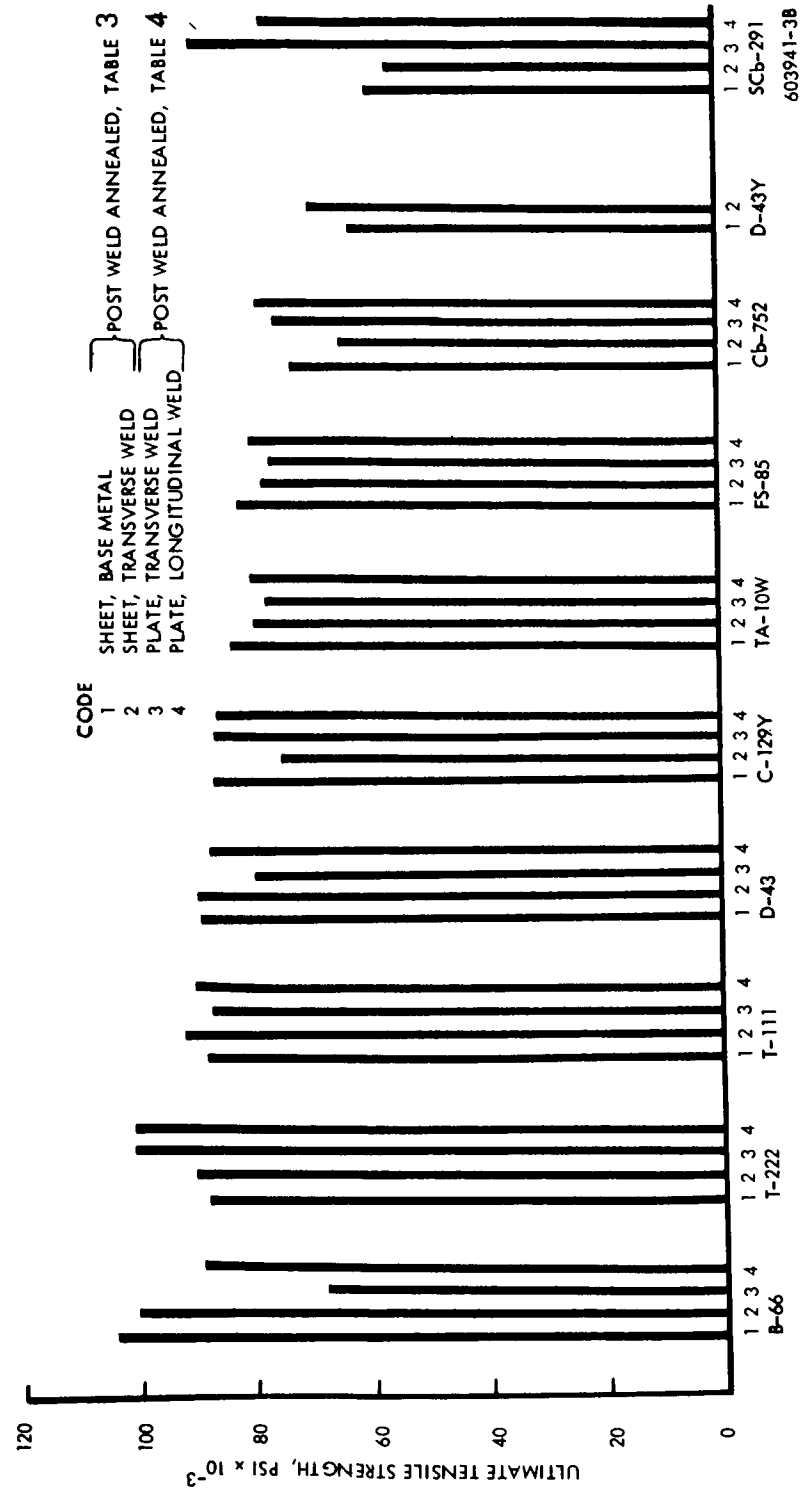


FIGURE 17 - Room Temperature Tensile Strength

T-222. This alloy also exhibited good ductility and proved nearly equal to T-111, while exhibiting greater strength. Slight weld surface tearing was noted in all the as-welded bend specimens. This was eliminated by post-weld annealing for one hour at 2400°F. The plate weld strength exceeded the sheet base metal strength for this alloy.

SCb-291. As expected, because it is solid solution strengthened and only of moderate strength, SCb-291 proved to be the most ductile columbium base alloy. The single failure occurring in this alloy was a full section fracture in a longitudinal specimen which bent through the nominal 140° before failure. The others, including two specimens stress relieved at 1900°F, produced defect free bends. A lower temperature anneal was employed for the plate than was used on the sheet since the higher temperature, 2200°F, might impair the ductility of this alloy through grain growth and it was felt that an overage anneal should be unnecessary. The differences in annealing temperatures may partially account for the lower tensile strength of the sheet as compared with the plate weld tensile strength.

FS-85. This alloy exhibited improved strength with a weld joint efficiency exceeding 90% while retaining reasonably good as-welded ductility. Both as-welded longitudinal bends failed at 40° and 125° by sudden severe transgranular cleavage. The cleavage failures are typical of columbium alloys. This behavior contrasts with the tantalum base alloys in which failures occurred as ductile tears indicating a total strain limitation rather than a loss of resistance to fracture propagation. Weld ductility was recovered by annealing for one hour at 2400°F. The annealed longitudinal plate weld tensile specimen had 21% elongation corresponding with the full ductile 140° bends obtained in the annealed welds.

C-129Y. As compared with FS-85, increased strength at room temperature is realized with a moderate loss in ductility. The ductility is recoverable through a 2400°F, one hour anneal. The as-annealed plate weld strength is at least equal to the annealed sheet base metal strength implying nearly a 100% joint efficiency. Weld bend test failures occurred catastrophically by full section transgranular cleavage as typical of the columbium alloys.

D-43. The strength of welds in this alloy is not significantly higher than for C129Y even though a more severe ductility loss is encountered which was not recovered by the single post-weld annealing treatment investigated. Strength and ductility in this system are dependent on the morphology of dispersed carbide precipitates which is controllable through heat treatment. Hence, the selected post-weld anneal is not likely to represent the optimum condition. Weld joint efficiency for the specific conditions of these tests was approximately 100%.

Cb-752. Plate weld ductility in this alloy is marginal in the as-welded condition, and also after annealing of 2200°F. As with D-43, there is no particular reason to assume that the single annealing treatment is optimum for recovery of ductility. The 2200°F anneal was chosen on the basis of the weld results in sheet material. EB weld results and data reported by Bewley and Schussler⁽⁶⁾ indicate that a 2400°F or higher anneal might have provided greater ductility recovery. Also, the annealed plate weld tensile strength is considerably higher than sheet tensile strength implying that overaging and full recovery of ductility has not been realized during the 2200°F anneal.

B-66. A minimal room temperature plate weld ductility was obtained in this alloy with only slight recovery resulting from a 1900°F stress relief anneal. Both tensile and bend test results indicated that the ductile-to-brittle transition temperature was above room temperature. The annealed transverse plate weld tensile specimen fractured with zero elongation at a stress level less than the transverse sheet yield strength.

CONCLUSIONS

- (1) Good weldability was exhibited by the second generation columbium and tantalum alloys as demonstrated by restrained weld tests and general accommodation in welding both sheet and plate. Few unusual complications arose within a nominal range of welding conditions even though weldability limitations were exceeded for several alloys.
- (2) Room temperature and elevated temperature weld strength approached base metal strength for all alloys demonstrating joint efficiencies at all temperatures of nearly 100 percent.
- (3) Welding resulted in a loss of ductility in all alloys as measured by the bend ductile-to-brittle transition temperature. The comparative degradation of ductility occurring with welding provides a convenient measure of weldability in these systems.
- (4) The range or total spread of weld transition temperatures obtained by varying welding parameters over a practical range also provides a measure of weldability. Considerable differences in this spread, which appears to measure alloy sensitivity to process variation, were noted between alloys.
- (5) Plate weldability was comparable to sheet weldability for the more fabricable alloys. However, with the less weldable alloys, adverse welding characteristics were exaggerated in plate welding.
- (6) Tantalum alloys were considerably less sensitive to welding than columbium alloys, and as a result have superior fabricability.

- (7) Columbium alloys generally require post weld annealing to improve weld ductility and enhance thermal stability.
- (8) As measured both by response to welding and post weld annealing, electron beam welds are more ductile and stable than TIG welds.

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